



Integrating soil and water conservation techniques in oil palm plantation management: A review of evidence-informed practices

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ABSTRACT

Soil and water conservation has been increasingly recognised as an essential element of sustainable oil palm plantation management in high-rainfall, complex topography erosion-prone soils landscapes. While considerable research has assessed individual conservation measures, evidence remains mixed across study design, spatial scale and environmental context with few broad syntheses focused on how measures work in concert within functional plantation systems. This review advances existing knowledge by synthesising recent empirical evidence to clarify how structural, vegetative, and landscape-level conservation practices operate across spatial scales and under different environmental conditions. A qualitative systematic literature review following the PRISMA framework analysed 36 peer-reviewed studies published between 2020 and 2025. Five thematic clusters were identified: erosion control, hydrological regulation, groundcover and organic matter management, landscape-level planning, and integrated agronomic and environmental impacts. Within diverse contexts, structural, vegetative, and landscape-level measures are often linked to soil stabilization and runoff mitigation benefits; however responses differ by site/ design. The synthesis emphasizes that methodological variations, site conditions and the necessity for maintenance substantially impact effectiveness as reported. By elucidating cross-scale interactions and implementation challenges, this review provides policy- and practice-relevant insights for developing tiered conservation planning strategies and evidence-informed best management practices within oil palm plantation systems.



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1. Introduction

Oil palm has become one of the most important economic commodities in the world as its cultivation has been globally expanded (Hanifa et al., 2023). Plantation expansion across diverse ecological zones was driven by increasing demand for food, bioenergy, and industrial uses, which has accelerated over the past two decades (Jijingi et al., 2025). Concurrently, increasing emphasis has been placed on aligning plantation management with long-term environmental resilience, especially in terms of soil and water resources controlling nutrient cycling, hydrological regulation, and land stability (Abdulaali et al., 2020). Soil and water conservation has become a major operational and policy priority within this sustainability agenda. Oil Plantations commonly grow in environments with heavy rainfall regimes, heterogeneous slopes, and erosive soils, leading to runoff and nutrient loss,

making this a context-specific conservation challenge rather than a uniform prescription (Oliveira et al., 2022; Firmanda et al., 2024).

To that end, broad ranges of soil and water conservation practices potentially contributing to sustainable oil palm management have been documented through research. Examples of these include structural practices (terracing, contour planting, check dams, silt pits), vegetative strategies (leguminous cover crops, understory regeneration, empty fruit bunches for mulching), and landscape-level measures such as riparian buffers, slope zoning, and watershed-oriented plantation layout (Sakai et al., 2022). The combination of these approaches is indicative of the multifaceted nature of plantation systems and the multi-scale need for integrated strategies to address soil stability and hydrological regulation in tandem rather than isolation (Abubakar et al., 2022).

Nevertheless, there is extensive heterogeneity in experimental design, scaling approaches, monitoring time scales, and performance metrics, which has complicated comparisons of reported performance across settings. Current studies have been conducted as field experiments, case studies, modelling analyses, and agronomic assessments reporting a range of indicators, including erosion reduction (e.g., soil moisture dynamics), sediment control (e.g., organic matter accumulation), or yield responses (Ngatiman et al., 2025). Since these indicators are quantified using different approaches and at different spatial resolutions, the evidence base remains challenging to amalgamate into unambiguous operational recommendations. As a result, plantation stakeholders do not have access to an integrated synthesis of the types of interventions tested, reported outcomes, and relevant contextual factors, all framed in terms of decision relevance.

Moreover, many studies are based on single interventions, such as individual cover crop species or different engineering structures, and pay even less attention to interactions among measures within an interlinked soil–water–crop system (Raketh et al., 2024). In production landscapes, stewardship practices function as interconnected elements that interact in ways that may not be congruent with their isolated effects. However, empirical evidence for such interaction effects is scarce and heterogeneous across study types, leading to uncertainty about the design of integrated management. Sustainability programs and the certification schemes, such as organic farming or climate resilience, that fall under their umbrella have also raised expectations for soil and water conservation as generic elements of good agricultural practice. National guidelines increasingly emphasize erosion control and hydrological protection (Attah, 2025). However, policymaking guidance is often based on broad guidelines rather than collated evidence about implementation environments, variation in effectiveness, and maintenance limitations.

This context presents an opportunity for a Systematic Literature Review (SLR) to provide a transparent and reproducible way to synthesise empirical and modelling evidence across different contexts. Accordingly, this review critically synthesises empirically evaluated soil and water conservation practices for oil palm plantation management, drawing on 36 studies identified in a PRISMA-guided systematic review. By bringing together intervention type, measured outcome, contextual conditions, and reported implementation restrictions, the synthesis facilitates informed decisions at both management and policy levels. Interpreting conservation practices across structural, vegetative, and landscape scales, the review also highlights methodological limitations and practical constraints that define implementation outcomes. The aim of this study is to review peer-reviewed evidence on soil and water conservation measures implemented in oil palm plantations, placing emphasis on their effectiveness, interactions, and implications for longevity. Accordingly, the review aims to address two research questions: (RQ1) Which conservation techniques have been defined and assessed empirically, and what have they achieved across what context; and (RQ2) How is soil stability within integrated management frameworks influenced by interactions of bottom-up structural, vegetative,

and top-down landscape-level approaches related to hydrological regulation? By synthesizing cross-system lessons on the importance of collaboration, the study seeks to generate evidence-informed insights to strengthen tiered best management practices and more context-sensitive conservation planning in oil palm systems.

2. Literature Review

A growing literature in sustainable oil palm management increasingly recognizes conservation of soil and water as key to the long-term resilience of plantations. Under varying rainfall regimes and topographic and soil conditions, research highlights biophysical hurdles to erosion, hydrological stability, and soil fertility. Rainfall regimes, topographic and soil conditions have invariably remained among the overarching elements of their conservation programs — structural engineering, vegetative cover, and landscape-level planning. Despite this breadth, the literature is heterogeneous in the methodologies deployed, monitoring time periods, and reporting of site conditions, which limits comparability between studies and reduces generalisability. These limitations indicate that many of the reported outcomes are context-dependent and difficult to extrapolate beyond plantation systems. This section, therefore, synthesizes conceptual patterns, areas of disagreement, methodological limitations, and unresolved gaps to frame the subsequent systematic synthesis.

2.1. Soil erosion and degradation dynamics in oil palm systems

Soil erosion in oil-palm plantation systems has consistently been identified as a significant limitation, particularly under humid, undulating conditions. The literature consensus agrees that young unmanaged plantations are particularly at risk due to soil exposure during early growth stages and soil disturbance during land preparation (Simarmata et al., 2025). This susceptibility is most prominent at moderate to steep gradients where accelerated runoff enhances sediment and organic matter export (Ashikin et al., 2019). However, rates of erosion reported from studies span a remarkable range (though in part this is due to the use of different monitoring periods and measurement approaches (for example, runoff plots, sediment traps, modelling outputs), making direct comparisons challenging and leading to significant uncertainty around the robustness of cross-site generalisations. This methodological variability underscores caution in interpreting reported erosion rates, as differences are more likely to reflect measurement protocols than fundamental environmental processes. High annual rainfall (> 2,500 mm) is often cited as a key driver of erosion risk in oil palm systems (especially where protective management practices are lacking) (Jayanti & Dewi Sartika, 2020). But there is a variety of conditions under which watersheds respond to erosive drivers, with research showing that rainfall intensity, event frequency, and soil texture and surface management matter as much or more than total rainfall. For example, clay-rich soils can become exposed, forming a sealing layer at the surface, which encourages runoff, while high levels of weed management have been shown to increase erosion as vegetation that provides soil stabilisation is removed (Hermawan et al., 2025). And few studies unpick these interacting variables precisely through tightly controlled comparative designs, making it difficult to

determine causal mechanisms from site-specific correlates. Soil organic matter as a mediator between erosion and hydrological behaviour (Azmeri et al., 2025). However, data on the trajectories of organic matter are limited, and when they exist, they mostly capture short-term results despite a paucity of baseline controls, which compromise the ability to assess whether soil effects observed in experimental studies are temporary or persistent for forest management purposes.

2.2. Soil conservation techniques: Structural and engineering approaches

It is well-recorded that structural conservation strategies mitigate erosion and regulate surface hydrology. Terraces are often observed to exhibit lower slope runoff velocity (Guillaume et al., 2018). However, effectiveness is rarely reported separately by slope class or rainfall regime, and many studies lack detail on maintenance frequency, cost, or long-term durability, thus limiting evaluation of operational feasibility. Consequently, the actual impact of systemic structural interventions remains largely unknown in many plantation scenarios. Soil conservation techniques describes broader, low-cost solutions like silt pits and infiltration trenches. But design parameters, spacing criteria, and performance metrics varied significantly across studies, and relatively few evaluations have lasted longer than a couple of years, limiting confidence in their effectiveness over time. Concerns reported in some research have focused on labour demand (Asad et al., 2024). Check dams reduce flow velocity (Nyasapoh et al., 2024). However, placement errors and sediment buildup may reduce efficacy over time, and many comparative studies provide little support for independent judgment on whether structural alternatives perform better than vegetative approaches at similar sites.

2.3. Vegetative conservation measures and soil organic matter enhancement

Vegetation-based approaches are widely discussed. Leguous cover-crops are discussed (Manorama et al., 2021). But reported-use results vary with the age of the plantation and rainfall regime, or with management intensity (some studies report trade-offs owing to competition for water or nutrients in dry periods), implying that cover-crop performance is context-specific or at least not universally useful. Mulching the cover soil (Sahari et al, 2020). However, the standardisation of both residue distribution and decomposition rates/nutrient cycling dynamics across studies is rare, leading to inconsistent conclusions about the magnitude of benefits from persistence. This discrepancy also partly reflects differences in the practices of measuring and managing residue across studies. Natural understory regeneration reduces erosion (Culman et al., 2019). However, empirical evaluations often focus on short-term soil measures (genus, species, and populations may also be calibrated), with insufficient evaluation across multiple operational scales, and mechanisation paybacks create uncertainty about how broadly applicable the findings might be.

2.4. Hydrological management and water conservation techniques

Hydrological regulation is a recurring theme in the literature, reflecting both excess runoff during wet seasons and moisture

deficits during droughts. Infiltration trenches between rows are commonly recommended to encourage infiltration and retain water between planting blocks (Ekaputra et al., 2020). Reported effectiveness, however, varies with soil type and rain regime, and several studies have found that poor maintenance can lessen long-term hydrological benefits. These findings highlight that hydrological outcomes are determined not only by the intervention design but also by subsequent operational and maintenance practices. Key elements for designing and maintaining drainage are repeatedly mentioned as determinants of the hydrological performance. Vegetated buffer strips along canals are commonly advocated to reduce sediment transport and improve water quality downstream (Rahman et al., 2019). Hydrological performance is quantified at various spatial extents (e.g., plot, block, catchment), making it challenging to compare studies and to ascribe observed changes in outflows or water balance to individual factors.

2.5. Landscape-level conservation and ecosystem-based approaches

Recent studies have suggested that, in certain contexts where broad landscape properties define hydrologic and erosion processes, intervention at the plot level may be insufficient. The use of riparian buffer zones (Cazier et al., 2024), assumed to act as sediment filters and stream bank stabilisers, is among the most well-studied landscape-scale interventions. At the same time, the diversity of recommended buffer widths and the challenges of reporting to enforcement speak to persisting uncertainties about the optimal design and implementation of plantation practices. For many of them, recommendations are based on studies at proprietary sites and cannot be directly transferred to plantations under different hydrological or regulatory conditions. Slope-based zoning is widely promoted as a means of appropriately adjusting management intensity to erosion risk. While some studies indicated lower soil loss when steeper slopes were protected (Jaroenkietkajorn & Gheewala, 2021). The other evidence suggested not take for granted an effective zoning and that slope risk of land degradation can only be minimized. If firstly terrain has to be evaluated accurately which means plantation operations would have to follow this plan, indicating thus at landscape level. While theoretically justified comes out with challenges of implementation which impact negatively its benefits appealing negative externalities to evolve.

2.6. Integration of soil and water conservation techniques

No single conservation action is found to provide a silver bullet solution to the suite of soil and water challenges arising from oil palm systems, a finding consistent across the literature. Although some structural measures reduce runoff yet do little to foster soil biological recovery, vegetative measures improve long-term surface stability at (relatively) small scales but may be ineffective when steep slopes or extreme rainfall occur. Consequently, several authors advocate the need for integrated frameworks that combine structural, vegetative, and landscape-level measures. However, recent empirical evidence directly comparing integrated approaches with single interventions in similar circumstances is virtually nonexistent, limiting our ability to assess potential synergistic benefits.

3. Methods

This study synthesises peer-reviewed evidence relevant to oil palm plantation management, which concerns soil and water conservation techniques, using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol to inform an SLR. This review synthesised secondary data from peer-reviewed journal articles listed on Scopus, including empirical field studies, modelling, and experimental assessments of soil and/or hydrological outcomes. Identification, screening, eligibility assessment, and inclusion at each stage were carried out using a priori-determined criteria to maximise rigour and replicability. The methodological framework was developed to allow a systematic search for relevant studies and to enable critical interpretation of the divergent methodologies in the included literature. A rigorous, systematic, structured data extraction and quality appraisal step was used in the review, ensuring that both synthesis and interpretation were commensurate with evidence coverage and variability in study quality.

The review process is detailed in Figure 1 and follows the PRISMA framework, which outlines the identification, screening, eligibility, and inclusion phases. The identification phase started with a Scopus search using the keywords “Oil Palm” AND “Conservation”, which returned 1,208 records. To increase specificity, an advanced Boolean search was used: (“oil palm” OR “oil palm plantation” OR “palm oil”) AND (“soil” OR “soil erosion” OR “soil conservation”) AND (“water” OR runoff OR “water management”) AND (“conservation” OR “management practices ”OR“ sustainable practices”). Making steps back excluded 1,087 records that

lacked an address to soil and/or water conservation practice in the oil palm system, leaving 121 records for screening. We identified studies using Scopus, a multidisciplinary database known for consistent indexing of peer-reviewed literature and standardized bibliographic metadata, facilitating transparent screening. However, using a single database may have excluded relevant studies indexed elsewhere, potentially introducing selection bias. Interpretation of the findings took this limitation into account to avoid overgeneralisation of the evidence base. The search and screening protocol was uniformly applied across records to reduce subjective inclusion determinations.

Records were limited to 2020–2025 during screening to identify recently published evidence relevant to current sustainability and plantation management practices, eliminating 58 records and retaining 63. One non-English article was excluded at the eligibility stage, resulting in 62 English-language papers. Subsequently, eligibility for full-text was assessed against an open-access/open-archive criterion to ensure methods and outcomes could be extracted readily/assessed across studies; this improves the transparency of evidence extraction but may introduce an accessibility bias by excluding paywalled studies. This compromise was deemed acceptable in order to allow full methodological verification of all included studies. After application of all eligibility criteria, 36 peer-reviewed studies were eligible for synthesis. To minimize the risk of over-representing comparability across designs of varying quality, this review treated outcomes as context-dependent and refrained from pooling effect sizes across incompatible measurement metrics.

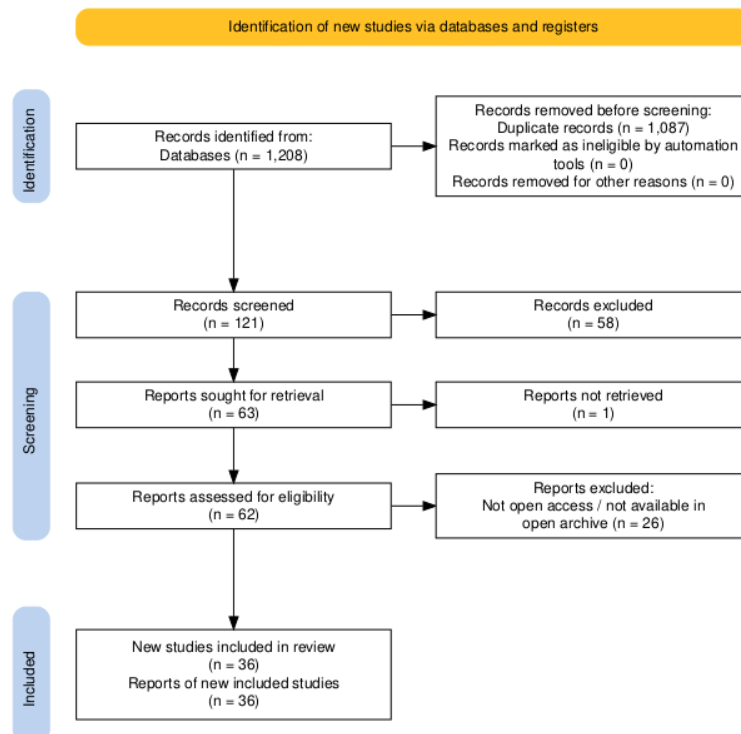


Fig 1. Systematic literature review process based on the PRISMA protocol

Mendeley Desktop was used to manage all bibliographic data, enabling citation tracking and duplicate detection. Full-text extraction for all 36 included studies was performed using a predefined template capturing: (i) study type (field,

experimental, modelling), (ii) site context (country/region, rainfall regime, slope class where reported, soil type where reported),(iii) conservation intervention(s) and scale (plot, block, landscape), (iv) outcomes and measurement approach

(e.g., erosion indicators; runoff/hydrological metrics; soil organic matter/structure indicators; yield or proxy agronomic measures); and (v) study duration and key limitations. Each study was also appraised for quality of evidence using a structured quality checklist designed for mixed-methods studies (e.g., clarity of reporting on methods and context; appropriateness of measurement; transparency of analysis; and acknowledgment of confounding factors). Quality ratings (i.e., high/moderate/low) were used to contextualise the strength of interpretation in the synthesis, not as hard exclusion criteria. This appraisal allowed the synthesis to consider differences not only in reported outcomes but also in methodological rigor across studies. Thematic synthesis was conducted according to an explicit, reproducible process: initial coding aggregated the interventions extracted from primary data under structural vs. vegetative vs. landscape-level categories; secondary coding aggregated outcomes into groups such as those of soil stability, hydrological regulation and broader sustainability indicators; and themes were iteratively refined through interstudy comparison to bring out areas of consensual finding and documented uncertainties or contextual limitations. In doing so, the review highlighted patterns of evidence while openly recognising methodological heterogeneity across the included literature. This method helps mitigate over-precision in specific comparisons across studies and yields a transparent evidence map of conservation practices by accounting for heterogeneity.

3. Results

We conducted a systematic literature review of peer-reviewed articles from 2020 to 2025, yielding 36 studies that met the inclusion criteria. The chosen studies cover a wide range of geographical regions, plantation types, and methodological approaches, including field experiments, observational studies, and modelling assessments. Because study designs, spatial scales (plot, block, catchment), monitoring durations, and outcome metrics varied considerably across studies, results are presented as context-specific associations rather than pooled effect estimates. Another methodological variation was evident in the study design, as well as in the choice of indicators, baseline definitions, sampling depth, and the duration of the findings observed, which were reported outcomes that affected the ability to analyze them. A thematic synthesis of the evidence revealed five themes: (1) soil erosion control measures; (2) improvements in groundcover plants and soil organic matter; (3) water management/hydrologic regulation; (4) regional conservation planning/buffer systems, and (5) integrated conservation benefits to productivity/sustainability.

Soil erosion control strategies were described in 29 (81%) studies, groundcover vegetation and soil organic matter enhancement was reported in 26 (72%) studies, water management and hydrological regulation was included in 24 (67%), integrated conservation effects on agronomic and sustainability indicators were noted in 22 (61%) studies, and landscape-level conservation planning occurred in 15 (42%) of the reviewed literature. These proportions represent the distribution of research effort rather than the relative efficacy or robustness of evidence for each type of intervention. Also, these indicate that the evidence base is especially concentrated at the plot and block scales, with fewer but more

methodologically heterogeneous studies conducted at the landscape scale.

The distribution suggests that erosion control, groundcover management, and hydrological regulation were the most common topics covered. Only some of the studies deal with landscape-scale planning and/or integrated agronomic and sustainability outcomes. These patterns reflect research attention, not causal importance, and need to be understood in light of differences in purpose, methods, and spatial focus. Specifically, the reviewed studies differ in whether outcomes were measured directly in situ (in end-user production environments), inferred from short-term experimental plots, or estimated using modelling approaches, which is important because it influences the strength and transferability of the reported findings. Thus, the theme overviews focus on (i) intervention types and scales, (ii) directions of reported outcome, and (iii) sites of heterogeneity that were recorded (e.g., rainfall regime, slope class, soil type, and monitoring protocol).

3.1. Soil erosion control strategies in oil palm landscapes

Soil erosion control is the most common outcome reported, with 29 of 36 studies having tested at least one indicator associated with soil erosion (Purnama et al., 2025). Reported erosion rates under unmanaged or minimally managed conditions vary spatially across mountainous terrain with 12–25% slopes and depend on site conditions, measurement methods, and monitoring duration (Wong et al., 2023). In general, compared to hydrological and physical properties of terrace and contour measures (i.e., various types and dimensions), their sediment loss is consistently reported as reduced across studies, although the reported magnitudes vary depending on slope gradient, rainfall intensity, soil characteristics, and study design (Afandi et al. 2023; Rahayu et al. 2025). Where erosion metrics diverge (e.g., plot-scale soil loss compared to sediment yield proxies), results are not directly comparable, and thus interpreted as directional evidence rather than uniform effect sizes. Also, the included studies differ in how erosion was measured (directly through field monitoring plots, sediment capture, or model-derived estimates), which influences comparability and the strength of inference.

Pruned fronds or empty fruit bunches are commonly reported as a mulch material for erosion mitigation. These studies report reductions in surface soil loss after mulch application, although the reported range is highly site- and time-dependent (Munévar-Martínez et al., 2025). Some improvements in infiltration and soil physical properties in the upper layer are also reported; however, the depth of measurements made, thickness of mulch applied, and length of observation differ considerably between studies, limiting direct comparison between reported orders of magnitude (Saidy et al., 2025; Siallagan et al., 2025). Baseline conditions and residue application rates were not consistently reported, making it difficult to determine whether differences in outcomes resulted from treatment effects or from differences in implementation. Reported mulch benefits should thus be understood as conditionally reproducible magnitudes; whether they occur in practice depends on application rate, residue placement, and local rainfall–soil conditions.

The reviewed studies report a wide range of engineering measures (i.e., silt pits, retention ditches, and check dams). Mediated effects include greater infiltration and higher runoff velocity, although design specifications, installation density, and evaluation methods differ across studies (Alhakim et al., 2025; Sutiarmo et al., 2022). The robustness of inferences, however, is not uniform across study types (field monitoring vs modelling), and reported benefits are sometimes based on predicted rather than directly observed hydrological responses. Results should be considered as context-specific rather than transferable (Comeau et al., 2021).

3.2. Water management and hydrological regulation

Water management and hydrological regulation are discussed in 24 studies that cover runoff control (Philip et al., 2023), soil moisture dynamics, and flow regulation (Gómez et al., 2023). Some reported challenges: excess runoff during wet seasons, localised flooding, and rapid drainage in some soil types. Conservation actions addressing these processes include a wide array of structural and vegetative measures, with reported effectiveness subject to environmental and management context. Hydrological responses are scale (plot, drainage network, or catchment) and rainfall-event dependent, restricting direct comparisons between studies. This heterogeneity is compounded by differences in moisture measurement depth, abstraction interval, and whether studies present event-based runoff, seasonal mean, or modelled hydrological response.

Multiple studies show that water-retention structures, such as inter-row infiltration trenches and small earthen dams, are associated with improved indicators of soil moisture. Reported changes in moisture are derived heterogeneously (Azizan et al., 2021; Greenshields et al., 2023; Lam et al., 2022) and vary across seasons, soil textures, and sampling depths. Some studies are based on short-term post-installation observation, while others report seasonal or multi-annual patterns, which inform the question of whether the reported benefits are immediate, serendipitous, or both. Consequently, these results are presented as suggestive of moisture benefits under certain combinations of soil–rainfall conditions rather than as a consistent magnitude applicable across plantation types.

Hydrological performance is also influenced by agronomic measures, such as cover cropping, alongside structural interventions. Leguminous cover crops, such as *Mucuna bracteata*, *Pueraria phaseoloides*, and *Calopogonium caeruleum*, have been shown to improve infiltration rates by 15–38% and lower runoff coefficients by 20–35% compared with bare-soil conditions (Abubakar et al., 2021; Sekyi-Annan et al., 2021). This root penetration further increases porosity, with some studies reporting a 9–14% higher available water-holding capacity, compared to traditional tillage, after two to three years of continuous cover cropping (Zhao et al., 2022; Riani et al., 2024). Nevertheless, these values are produced in distinct baseline soil conditions, cover establishment elevations, and sampling procedures. Reported values are presented as reported ranges rather than pooled estimates due to differences in protocols and baseline conditions.

Highly applicable to vegetated buffers, drainage management practices are reported to reduce suspended sediment loads and improve water quality downstream (Dearlove et al., 2024; Abdullahi, 2025). Reported results vary with drainage design

and maintenance regimes, highlighting that hydrological regulation outcomes are determined by the combined implementation of multiple conservation measures rather than isolated interventions. However, few studies track downstream effects over multi-decadal periods, limiting ecological inference about persistence and off-site benefits at the watershed scale. This is especially important given the inconsistent measurement of downstream indicators compared to plot-level indicators, which provides a weaker empirical basis for watershed-scale conclusions.

3.3. Groundcover vegetation and soil organic matter enhancement

A further major theme concerns vegetation's contributions to soil organic matter, surface soil stabilization, and nutrient cycling. Natural regeneration (Johari et al. 2020), leguminous cover crops, and mixed understory management are methods to maintain or instate groundcover vegetation, accounting for 26 studies. However, the duration of studies and depth of sampling vary, and many outcomes are captured at short-to-medium time horizons, which limits interpretation around long-term soil recovery. Groundcover vegetation is frequently linked with increased Soil Organic Carbon (SOC) accumulation. In various studies, SOC scores have been reported to increase by 0.25% to 0.65% over 2–3 years, representing a 12%–28% increase from baseline (Budiman et al., 2020; Ramadhan et al., 2021). Long-term management of cover crops for more than 5 years can, in some cases, boost SOC by as much as 0.9% (Susanti et al., 2021). Due to the use of varying depth intervals and baselines across studies for SOC measurement, these values should be considered reported ranges (rather than directly comparable effect sizes). Differences in soil sampling depth, baseline reference conditions, and plantation age further complicate direct attribution of SOC gains to vegetation management alone. Biomass accumulation is another important factor. Above-ground biomass production of leguminous cover crop systems ranges from 4.2 to 6.8 tons/ha/year, while nitrogen fixation capacity varies from about 45 kg N/ha/year (low stand density) to over 110 kg N/ha/year (high stand density), depending on the species and population composition used (Popkin et al., 2022; Jam et al., 2025). These inputs are integral to nutrient cycling. However, estimates are based on different measurements and modelling assumptions and are not consistently aligned with fertiliser-reduction outcomes across studies.

Besides vegetation management, studies investigating natural understory regeneration indicate that selective regrowth is claimed to diminish erosion by 18–32% and increase litter mass by 1.5–2.3 tons/ha after one year (Anggat et al., 2024; Bautista et al., 2024; Egbunike et al., 2023). In addition, macrofauna abundance is higher in groundcover vegetation (Suliman & Kassim, 2022). However, these results are usually derived from site-specific comparisons, and operational trade-offs (e.g., access and competition when young palms) are rarely observed in empirical designs. Thus, the evidence supports a greater contribution to short-term ecological benefits than to extended leaf longevity and operational efficiency. Together, this theme emphasises that vegetation-based conservation approaches may complement structural interventions. However, cost-effectiveness claims are not consistently substantiated, as cost accounting and labour

requirements were inconsistently reported across the documents reviewed in this study.

3.4. Landscape-level conservation planning and buffer systems

The fourth theme is conservation at the landscape scale. Fifteen studies highlight that interventions at the plot level may be inadequate, especially in heterogeneous landscapes or near riparian systems (Hermawan et al., 2020). This includes field and modelling studies, which differ in the strength of inference when validating measured or predicted outcomes. One of the most commonly agonized over details is riparian buffer zones. Buffer widths of 10–30 m are reported to cause reductions in sediment transport between 35 and 62% along with an increase in riparian vegetation recovery after two to four years (Suryatmojo et al., 2020). Nevertheless, buffer design parameters and compliance conditions are reported inconsistently, and width recommendations vary widely among settings, limiting the transferability of specific numeric ranges. Furthermore, some reported effects are based on indirect sediment indicators or on modelling of regional landscapes and have not been field-validated over extended time periods.

Associating soil and water outcomes with conservation-oriented land-use planning that includes block arrangement and harvesting path design. For example, it has been found that repositioning harvesting rows across the slope decreases runoff velocity by between 14 and 22% and increases infiltration by between 8 and 12% (Satriawan et al., 2021). Europaeus and Janhunen (2017) reported erosion reduction of 56–73% from plots with terraced landscapes combined with vegetative buffers compared to those without the intervention. Because these studies differ in both baseline conditions and measurement methods, these values are interpreted as reported ranges rather than directly comparable estimates of interaction effects. The other major component is slope categorization and variable treatment. It was reported that average annual soil loss is decreased by 32–49% in slope-sensitive protocols than non-differentiated systems adopted plantations (Saad & Junedi, 2022). All that said, the extent to which these outcomes are contingent on enforcement, upkeep, and operational compliance is not uniformly measured across studies. The landscape-level evidence base is consequently limited not only in the number of studies but also in study design variation, modelling reliance, and inconsistent reporting of implementation conditions.” These findings highlight that landscape-level planning could be effective in maximizing the impact of plot-level interventions. However, the evidence base is smaller than what we described for plot-scale studies and more heterogeneous in methods, suggesting landscape-level effectiveness should be considered both promising but context-variable.

3.5. Integrated conservation impacts on agronomic performance and sustainability indicators

Beyond the biophysical outcomes, 22 studies investigated wider agronomic and sustainability considerations. While measures are primarily aimed at protecting soil and water, studies show that they also confer indirect benefits for palm growth and nutrient availability. However, agronomic benefits are described according to different yield metrics, time horizons, and baselines, which limits comparability and may

partially account for heterogeneous findings. Yield responses vary with soil type, conservation intensity, and plantation age. Across studies, yield gains attributed to integrated conservation are reported to range from 3% at 3 years to 12% at 5 years, with the greatest gains observed in plantations previously exposed to erosion or high runoff (Fiantis et al., 2024). According to some long-term studies, root length density is reported to be 10–18% higher in systems under groundcover vegetation or mulch. Few studies use controlled comparative designs; however, this makes it difficult to isolate the effects of agronomic improvements from those of individual measures, combined interventions, or broader site management. Such values are reported as ranges; hence, extensive controlled comparisons do not allow for attributing yield changes to specific intervention components.

Several studies highlight cost-related outcomes. The use of cover crops has been reported to reduce herbicide application by 25–40%, while organic mulches are claimed to lower fertiliser expenditure by 10–18%. Structural interventions involve up-front labour investment, with some reporting cost recovery within 2–3 years (Murga-Orrillo et al., 2024). Nevertheless, cost estimates are poorly documented; they typically relate to specific contexts and rarely capture standardised accounting of labour, transport, and maintenance that would allow for generalisation across types of plantation. Environmental sustainability metrics are on the rise. Suspended sediment concentrations are reported to be reduced by 30–58%, turbidity decreased by 20–44%, and soil biodiversity indices improved by 15–28%, depending on conservation intensity (Yunus et al., 2022). Indicators of environmental sustainability are on a positive trajectory. Suspended sediment concentrations decreased (30–58%), and turbidity decreased by 20–44%, with soil biodiversity indices improved between 15–28%, depending on conservation intensity (Lestari et al., 2022). However, these indicators are defined and monitored differently across studies, and the assessment duration is often too short to determine whether benefits are sustained under variable climatic conditions.

Across the themes, the studies reviewed suggest that conservation practices are assessed more in combination than in isolation. Numerous studies claim that integrated measures lead to better soil and hydrological indicators, but the extent and duration of reported effects depend on context and study design. This variation reflects not only the environmental differences but also considerable heterogeneity in study duration, monitoring scale, indicator selection, and type of inference made (observed versus modeled outcomes). As such, the Results reveal trends in reported efficacy but do not address consistent performance. In light of heterogeneity in methods and metrics, results should be viewed as an evidence map of intervention–outcome associations rather than a meta-analytic estimate of effect size.

4. Discussion

Our systematic review results indicate that new research surrounding soil and water conservation strategies in oil palm plantations has become increasingly abundant and diverse (field experiments, observational studies, or modelling assessments). Across the 36 studies include for analysis, conservation practices protecting the soil are typically organised into structural, vegetative, and landscape-level

domains, with mixed outcomes identified across biophysical settings, intervention designs, and measurement approaches. Rather than repeating the reported results, this Discussion extracts what these observed patterns may mean for implementation, understanding evidence, and decision-making in operational plantation conditions. Thus, this Discussion interprets patterns emanating from the synthesis while recognizing heterogeneity, differences in the strength of inference across study types, implementation constraints, and context-specific trade-offs when considering the two research questions.

4.1. Empirically evaluated conservation techniques and their quantifiable outcomes (RQ1)

1. Structural conservation measures

The data set ‘structural techniques’ is by far the most documented, with codes for terrace, micro-terraces, silt pits, bunds, retention ditches, and check dams recorded. Across the majority of studies, these interventions are associated with lower erosion indicators and higher infiltration or runoff control, especially on slopes (Asmara & Randhir, 2024; E. Al-Esawi et al., 2021). However, due to variable slope classes, rainfall regimes, monitoring durations, and outcome metrics used in the literature, the reported effect sizes are not directly comparable. Consequently, the evidence is discussed more in terms of directions and performance conditions as mapped, rather than in uniform magnitudes. Furthermore, some interventions are sensitive to design specifications and maintenance quality, suggesting that implementation fidelity is a critical precursor to effectiveness (Meijide et al., 2020). This has significant implications for practical applications: structural interventions may appear to work in a technically sound environment, but their performance in the field can deteriorate rapidly when maintenance schedules, labour, or engineering supervision are lacking.

Reported hydrological outcomes for structural measures predominantly suggest that runoff has been attenuated and local water retention has been improved, even in channel-based structures, such as check dams (Bakar et al., 2025). However, hydrological indicators are reported in heterogeneous ways (e.g., plot-scale runoff vs channel sediment load vs modelled discharge), preventing cross-study generalisation. Universal claims of operational compatibility should be viewed with skepticism, as noted, because costs, maintenance burden, and disruption to harvesting logistics are unevenly reported (Lalruatkimi et al., 2025). Where deficits are acknowledged, the most common implementation constraints reported are sediment infilling, occasional need to be re-excavated, and labour requirements that may be harder to meet in smallholder contexts or low-mechanisation environments. This pointed out that structural interventions must be assessed with respect not only to the initial biophysical performance but also to the required maintenance input, adaptability to harvesting operations, and costs under various plantation ownership arrangements.

2. Vegetative conservation measures

The second major cluster of interventions, vegetative approaches, includes Leguminous Cover Crops (LCC), natural vegetation strips, mulching, understory management, and riparian vegetation retention. LCC is one of the most

commonly evaluated practices and is often linked to lower erosion and improved soil condition indicators (Vijarnsorn, 2021). However, reported benefits vary widely between species selection, establishment success, estate age, and climatic context. It remained especially inconsistent regarding background trade-offs, such as competition for moisture during dry periods, establishment failure probability, and added management complexity (Turjaman et al., 2024). Instead, from a management perspective, vegetative measures are not low-cost or self-sustaining alternatives; they depend on establishment success, follow-up management, and adaptation to local moisture regimes to work reliably.

Notably, frond or empty fruit bunch mulching is often associated with indicators of enhanced soil moisture and physical condition (Chaddy et al., 2021). At the same time, evidence is mixed regarding the consistency of benefits across sites, in part because residue application rates, spatial distributions, and decomposition conditions differ. Scalability, especially outside larger estates, may be constrained by practical considerations such as residue transport, labour inputs, or uneven field coverage. Notably, few studies report the application rates, labour time, or transport distance in a standardised manner so that reported biophysical benefits can be translated into operational recommendations. Consequently, the practical value of mulches cannot be assessed solely on the basis of biophysical effects; it also depends heavily on residue availability, transportation infrastructure, labour allocation, and the plantation's capacity to accommodate repeated applications over time.

Riparian buffers, though less commonly assessed than plot-level measures, are generally associated with sediment capture and better water-quality proxies (Patah et al., 2025). However, effectiveness is contingent on width, vegetation type, upstream land management, and enforcement, and these conditions are inconsistently stated. Ecological co-benefits are reported, but in general, measures are indirect or short-term (Ewane, 2021). Thus, buffer recommendations should be seen as conditional design guidance rather than hard standards unless backed by context-dependent monitoring and compliance mechanisms. This suggests that buffer policies should never prescribe width in isolation, as they must integrate site-specific hydrological risk, monitoring needs, and enforcement capacity.

3. Landscape-level conservation measures

Landscape-scale interventions consist of contour-aligned block designs, integrated drainage networks, terrain-based zoning, and coordinated watershed-level planning. Supporting evidence from modelling studies (SWAT, WEPP, InVEST) indicates that spatial planning can reduce predicted erosion hotspots and downstream hydrological outcomes (Nugroho & Wakhid, 2024). However, model results depend on data quality and the assumptions made about parameters and calibration; hence, they should not be regarded as comparable to in situ-measured effects. A further limitation is that many studies do not describe calibration against long-term monitoring data, undermining confidence in transferability across regions. And the limited evidence on feasibility, opportunity costs, and compliance where zoning recommendations are proposed (Shaha et al., 2024). Modelling and case-based studies predominantly regard an integrated basin-scale drainage design as impactful for

stormwater regulation (Nasi, 2023). However, the quality of the evidence is heterogeneous, as many investigations assess hydrological performance across disparate temporal scales and rainfall event definitions. Although coordinated planning may help reduce flooding and vulnerability to droughts, the literature offers scant empirical assessment of long-term maintenance, governance needs, or the distribution of costs—factors that matter for implementation across a mixed-ownership mosaic (estates versus smallholders). Therefore, landscape-level options must be interpreted as promising but implementation-dependent since they require institutional capacity to schedule maintenance, coordinate across blocks, and enforce. In practice, this implies that landscape-level conservation is as much a governance challenge as a technical one, given that effectiveness depends not only on coordination across plantation blocks and consistent compliance but also on the equitable distribution of implementation costs.

4.2. Interactions among structural, vegetative, and landscape-level approaches (RQ2)

1. Synergistic effects on soil stability

The combination of structural and vegetative measures has been reported to have greater impacts than single interventions, such as terracing with leguminous cover crops (Babalola et al., 2023). However, the evidence base rarely includes like-for-like designs that directly isolate by-design interaction effects imposed under equivalent site conditions, precluding a robust quantification of “synergy” between studies. Mechanistically, terraces alter hydrology on the slope, and vegetation increases surface cover through anchored roots; even mulch can further mediate infiltration or seal the uppermost surface (Razali & Lion, 2021). While their interaction pathways are realistic, the realized benefits depend on establishment, persistence, and local rainfall–soil regimes (Razali & Lion, 2021). By this line of thinking, integration is viewed descriptively as a mechanistically validated strategy that allows for various empirical designations, rather than consistently as a well-established “more-than-additive” effect. This distinction is critical to practice, as integrated systems should be presented as context-dependent management bundles that require adaptive enactment—and not as universally superior packages that perform equally well across all plantation contexts.

Spatial placement of interventions (e.g., landscape zoning) may enhance co-benefits by targeting sensitive areas for erosion control or hydrology improvements (Razi et al., 2025). However, corroborative evidence is limited, and some allegations are based on modelling rather than long-term ground-truth validity. Informed placement relies on robust land assessment and operational alignment — neither of which is usually generalized. This matters a lot because zoning effectiveness depends on enforcement and continued monitoring beyond biophysical suitability. In settings where mapping, compliance, and monitoring systems are poor, targeted integration may not be fully realised in practice.

2. Hydrological regulation through integrated management

Integrated conservation affects hydrology through complementary mechanisms: structural interventions reshape runoff routes, vegetative coverage changes infiltration and roughness properties, and landscape planning determines flow

connectivity. However, results are sensitive to measurement scale, rainfall-event characteristics, and duration of monitoring, and should not be interpreted as a uniform magnitude of improvement. Plot-scale evidence indicates that peak runoff is lower under combinations (Yeo et al., 2020), but caution is needed when extrapolating to plantation-wide hydrology, particularly in studies lacking long-term catchment monitoring. Hydrological “success” should therefore be considered scale-dependent (plot versus downstream effects) and verified with appropriate monitoring indicators commensurate with the targeted management scale. For managers and policymakers, this means assessing the success of intervention against well-defined spatial objectives, such as solving on-site runoff problems, protecting drainage networks, or improving downstream water quality.

Long-term modelling studies indicate that integrated measures may mitigate seasonal extremes (Rathore et al., 2019). But outputs depend on assumptions, and very few studies triangulate predictions with long-term field observations. Such trade-offs — for example, if waterlogged areas developed locally in poorly drained soils or drainage patterns changed to the detriment of downstream users — are rarely considered. This limitation suggests that IHM should consider boundary-aware impacts (within the plantation and off-site) rather than relying solely on plot-level indicators. Finally, it indicates that if integrated hydrological strategies are to be sustainable tools for robust long-term planning, monitoring frameworks must reflect unintended consequences as well as intended benefits.

3. Improving plantation sustainability through combined approaches

Multi-component frameworks are sometimes associated with improved sustainability outcomes, though the strength of the evidence varies by design and metric. Such results should be interpreted cautiously because many studies evaluate interventions over short time frames. A joint landscape planning study reports less concentrated erosion and greater watershed stability (Verchius et al., 2025; Bano et al., 2025), although little verification has been conducted across complete plantation cycles. The lesson, then, is that sustainability claims look best when cast as risk reduction and resilience enhancement, wrought under conditions of continued maintenance and monitoring. Such framing is better suited to domains of policy and certification, in which asserted effects must be linked to ongoing verification of those claims rather than inferred from conservation actions per se.

Some researchers say there are operational benefits, including reduced sediment accumulation on surfaces and in stormwater collection systems. Some economic data are limited, and only a minority of studies report clear cost accounting, labour inputs, or sensitivity analyses. Cost-effectiveness is typically assessed using a suite of capital availability, labour capacity, and institutional support (Anyaoa & Zhang, 2021) when it is alleged. This can be a major impediment to decision-making, as technically sound interventions may still not be feasible when labour and capital are in short supply or maintenance responsibilities are unclear. To aid decision-making, future evaluations should report standard cost components (e.g., installation, routine maintenance, labour time, and material transport) and the different feasibility of estates relative to smallholders.

In summary, the literature supports the argument that a combination of structural, vegetative, and landscape-level measures can simultaneously meet multiple soil–water process needs. But the strength of evidence showing “more than additive” effects is constrained by heterogeneous methods and a lack of controlled comparative studies. Hence, integration is articulated as an evidence-based, mechanistically plausible pathway whose execution should be monitored and whose performance should not be assumed to be superior across contexts. The primary implication is that integrated conservation must be operationalised as an adaptive management approach, in which interventions are selected and adjusted based on terrain (e.g., clay content or slope), hydrological sensitivity (e.g., highly fractured areas), labour capacity, and maintenance feasibility.

The synthesis suggests that integrated conservation is often associated with improved soil and hydrological indicators, as well as potential co-benefits for agronomic performance and environmental stewardship. However, benefits are context-dependent and constrained due to feasibility, sustainability, and cost. A number of practical and policy implications arise, particularly regarding the translation of evidence into tiered planning guidance rather than blanket prescriptions. These implications become more pertinent as policy frameworks and certification schemes strive for auditable conservation quality standards that remain viable across the range of plantation contexts.

First, early incorporation of conservation measures during plantation establishment can minimize challenges later during retrofitting. Business prospects, however, are not the same everywhere: they depend on geography, availability of office workers, and level of mechanisation and maintenance capacity. As such, conservation is best framed as a component of the system that depends on planning—the fit of its implementation varying between estates and smallholders. Installation should thus be closely aligned with early-stage planning, which should also specify maintenance routines (e.g., re-excavation, residue replenishment, buffer protection). This shifts conservation away from a reactive band-aid and toward an integral design principle baked into the plantation's development.

Second, this evidence base can inform Best Management Practices (BMPs) by identifying which types of interventions are frequently evaluated and the conditions under which they tend to succeed. BMPs should also provide tiered, condition-based (e.g., slope- and soil-dependent) options to avoid over-standardisation, with clearly defined maintenance needs and monitoring indicators. In practical terms, this translates to bundling minimum BMPs by terrain class (e.g., cover + contour structures on moderate slopes; terraces + cover + drainage controls on steeper slopes) and correlating each bundle with measurable indicators (sediment, turbidity, proxies for soil cover and infiltration). This tiering is a key practical contribution of this review, as it converts heterogeneous evidence into decision-relevant guidance rather than universal prescriptions.

Third, watershed-focused planning—such as riparian buffer regulation, slope-sensitive vegetation planting, and the spatial coordination of structures—is also indicated. But evidence for longer-lasting landscape-scale benefits is patchy, and often

based on modeling rather than short-term indicators. Hence, discussions of policy recommendations should combine spatial rules (e.g., buffers and zoning) with governance and monitoring arrangements, such as routine compliance checks and downstream water-quality metrics that can provide evidence of effectiveness over time. Without such verification systems in place, landscape-scale conservation may be more aspirational than operationally efficient.

And finally, quantitative indicators (e.g., sediment control measures, hydrological metrics, and soil condition proxies) can support sustainability certification and compliance monitoring. However, indicator selection should pragmatically account for feasibility and comparability across plantations, and certification claims should acknowledge uncertainty when metrics are non-standardised or lack a long-term verification pathway. Utilising a small number of harmonised, auditable indicators can increase policy uptake by associating conservation actions with measurable outcomes (rather than process-only compliance). This is a more robust policy approach than simple prescriptive rules, since it links conservation performance to verifiable, reviewable evidence.

While the evidence base has grown, several gaps remain that inhibit decision-making. These include limited long-term monitoring of integrated metrics, poor reporting of site context, and a lack of comparable economic evaluations across plantation types. Future studies should focus on designs that report implementation costs, maintenance requirements, and even performance under extreme rain events, in addition to standardised measurement protocols that allow for comparison across sites. Methodological innovation (for example, integrating remote sensing with hydrological monitoring and model calibration) could enhance landscape-scale inference. In conclusion, bottom-up cross-regional comparative studies remain needed to test transferability across Europe and to disentangle context-specific effects from more generalisable mechanisms. Filling these gaps could greatly enhance the value of future evidence for plantation managers and policy actors seeking conservation solutions that are practical, scalable, and verifiable.

5. Conclusion

This systematic review synthesises new peer reviewed evidence and identifies soil and water conservation in oil palm plantations through a review of 36 papers in the literature published between 2020-2025. The literature highlights conservation practices across three levels: structural (focused directly on the soil/field), vegetative (including natural vegetation) and landscape-level interventions, each targeting different soil/to filtering processes. Because the review is not about individual effect sizes, it instead describes how these domains behave across scales (from plots to landscapes) and under which environmental and management conditions they are most often reported to be effective. Effectiveness is not uniform; reported outcomes vary by site conditions and study design. As the review notes, conservation practices are usually applied and tested in combinations, rather than in isolation.

Although several studies have shown beneficial changes in soil and hydrological indicators from integrated approaches, the strength of evidence for interaction effects is highly variable across studies, hampered by different data collection methods and the absence of controlled comparative designs.

Integration, hence, needs to be regarded as supported and sound administration rather than a final universal remedy. This is important for informing policy and certification mechanisms, as additive or synergistic benefits cannot be presumed without site-specific verification and monitoring. Therefore, part of our hope is that the main contribution of this review may be to not only summarize recent evidence but also synthesize it into a cross-scale, decision-relevant framework that connects elements of conservation measures with implementation conditions and monitoring needs. More broadly, this review contributes to the environmental and water engineering literature by systematically providing an evidence base that links intervention classes, spatial scales, and reported outcomes — with a view toward progressive evolution from descriptive listings of interventions to context-conditional design best practices.

The results underscore the need for tiered, site-specific conservation design (rather than one-size-fits-all prescriptions) that carefully considers estimates and balances metrics such as local topography, rainfall regime, and maintenance capacity; they may help inform practitioners and planners in prioritizing management actions across diverse communities. That should practically manifest as conservation “bundles” by slope class and hydrological sensitivity, with their implementation tracked through prescribed maintenance routines and performance metrics. This review emphasizes that spatial planning rules should integrate realistic auditable into systems of policy and certification for assessing conservation performance based on verifiable outcomes, rather than relying on an inferred conduct mechanism within land-use plans. For researchers, the synthesis demonstrates a need for longer-term, context-specific and economically transparent evaluations delivered through ‘standardised’-cost reporting and harmonised monitoring protocols that can generate more robust decision-making frameworks that underpin sustainable oil palm plantation management. Collectively, these insights position the review as a resource for improving the effectiveness of concerted conservation action in oil palm systems.

Study Limitations

Several limitations to the interpretation of the findings from this systematic review should be acknowledged. The review was limited to Scopus-indexed open-access literature; it may have missed relevant studies published elsewhere or behind paywalls. While this methodology helped ensure that full-text materials were open and available for verification, it poses the risk of a biased database, and as such, a bias against accessible texts. Second, there is high heterogeneity in the methods used in the studies we reviewed; differences include study design and spatial scale (e.g., plot-scale, plantation block, or catchment), as well as the duration of monitoring and measurement protocols. This degree of heterogeneity restricted comparability of the reported outcomes and precluded formal meta-analysis. Third, the preponderance of research is underpinned by short- to medium-term monitoring efforts, which limit our ability to assess the long-term effectiveness and longevity of conservation interventions across spatially heterogeneous climatic and management gradients. Finally, the operational and economic dimensions of

conservation practices (e.g., installation costs—materiel, labour, and maintenance requirements) are also unevenly documented across the studies available to us. This limits the comparability of results relating to cost-effectiveness and practical viability across different plantation contexts.

Recommendations for Future Research

The synthesis identified critical knowledge gaps to be addressed by future investigation. First, long-term data are required to evaluate the persistent effect of conservation practices in complete plantation cycles during abnormally high precipitation events. Second, future efforts should employ standardised measurement protocols that include harmonised indicators of rates of land- and water-mediated soil erosion (drainage basin-related soil organic carbon) with a focus on hydrological regulation, as well as improvements in organic carbon and water quality. More standardisation would facilitate comparability across sites and enable stronger quantitative synthesis. Third, more studies included economic and operational analyses, such as transparent reporting of installation costs, maintenance requirements, and labour needs beyond cost–benefit trade-offs. All these aspects are important for evaluating the feasibility of both estate and smallholder systems. Fourth, even though plantations are location-specific, future work may also consider landscape-scale conservation that integrates field-level monitoring data with more remote sensing and hydrological modelling to assess the interactions between plantation management measures and watershed processes. Finally, comparative analyses across regions would help us disentangle between context-bound results and more generalisable mechanisms that regulate soil and water conservation in oil palm systems.

Practical and Theoretical Implications

Practical implications

These findings provide evidence-based guidance for plantation managers, policymakers, and sustainability certification systems. Thus, the review suggests that conservation practices be implemented through tiered, site-specific approaches rather than one-size-fits-all prescriptions. Structural, vegetative, and landscape measures are most effective when selected based on topography, rainfall regime, and hydrological sensitivity. Doing so might help conservation design make optimal use of bundle approaches (maximizing groundcover management and contour structures such as matching drainage control systems to slope classes and rill/gully/ground erosion risk levels) as well as costly but maximally effective approaches. Furthermore, it was formed through a makeup maintenance strategy of sedimentary deposition and extraction, with supplementary deposits added as needed and shrub clearing. This information is particularly timely for biophysical data requirements associated with Best Management Practice (BMP), sustainability certification, and plantation planning frameworks, as they seek to balance environmental protection with operational viability. rational viability.

Theoretical implications

Conceptually, this review advances environmental and water engineering literature by recognizing soil and water conservation in oil palm systems as a multi-scale management challenge rather than isolated interventions. The synthesis

stresses that conservation practices should be evaluated across interacting spatial scales, from plot-scale interventions to landscape-scale hydrological controls. This review advances the conceptualization of interactions among multiple conservation mechanisms within a complex plantation system by integrating evidence from structural, vegetative, and spatial planning measures. Moreover, this study underscores the need for implementation-oriented environmental research — in which technical effectiveness and the institutional, economic, or operational barriers to adoption are evaluated in practice.

Statements and Declarations

Data availability statement

There is no primary empirical data collection in this study; the only data are secondary, peer-reviewed journal articles included in a systematic literature review. All 378 analysed sources exist in the Scopus database and are freely accessible to users from the respective publishers. Full references of studies included in the analysis can be found in the reference section of this manuscript. No primary data were generated during the course of this research. Any additional data regarding study selection, screening process, and extracted variables will be made available by the corresponding author upon reasonable request.

Conflicts of interest declaration

The authors declare that there are no conflicts of interest associated with the publication of this manuscript. The research was conducted independently, without any commercial or financial relationships that could be perceived as potential conflicts of interest.

Author contribution

Author contributions to this manuscript are as follows:

- Conceptualization: LJ
- Methodology: LJ
- Literature Search and Data Curation: LJ
- Formal Analysis and Synthesis: LJ
- Writing – Original Draft Preparation: SN
- Writing – Review and Editing: SN
- Supervision: LJ.

All authors have read and approved the final version of the manuscript.

AI usage disclosure

AI-assisted language tools were used during the preparation of this manuscript; however, they were used only to enhance aspects of text clarity and editing. These tools were not employed in data analysis, selection of literature, or interpretation of findings. All intellectual content is the responsibility of the authors.

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