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Navigating hydrological governance and adaptive water-management strategies in oil palm plantations: A systematic literature review

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ABSTRACT

Water resource management in oil palm plantations is a core topic in contemporary discussions on sustainable development, requiring a balance between the benefits of production landscapes and ecosystem stability. However, existing studies are scattered across the fields of hydrology, agricultural engineering, soil science, and governance, making it difficult to form an integrated understanding of management strategies adapted to different biophysical and climatic conditions. This gap has restricted the advancement of practical work in this field. To address this problem, this study conducts a systematic literature review of hydrological governance and adaptive water resource management strategies for oil palm systems, aiming synthesize and integrate contemporary scientific evidence on water resource management challenges and best practices for oil palm plantations, and to develop an integrated understanding of hydrological processes, management strategies, and environmental impacts. This study adopts the systematic literature review (SLR) method following the PRISMA protocol, using peer-reviewed articles indexed in Scopus and published from 2019 to 2025. Using pre-defined screening criteria including keywords, publication year, language, and open access status, the study identified 35 eligible studies, which are analyzed using thematic synthesis. The coding categories covered eight domains: hydrological change, irrigation and water use efficiency, drainage performance, groundwater regulation, water quality, soil and water processes, climate-related risks, and best practice measures. The study also identified five core research themes and four types of best practices reported in the literature.

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Introduction

Attah et al. (2025) proposed that water [MS1.1] resources are a core strategic element of contemporary tropical agricultural landscapes, holding the dual value of supporting ecological functions and ensuring the long-term economic viability of plantations. Lyu et al. (2025) pointed out that three factors—rising climate variability in the humid equatorial zone, intensifying land conversion, and updated environmental regulations—have elevated water resource governance to a core position on the agenda of agricultural policy and industrial practice. Abubakar et al. (2022) stressed that for countries that rely on perennial crops to drive rural development, water management requires mastery of three cross-domain bodies of knowledge: hydrology, soil and water processes, and the environmental externalities of large-scale cultivation. In the context of oil palm production, water accessibility is linked to multiple core industrial and ecological indicators. This paper argues that water management is by no means a single technical issue, but rather a multi-dimensional integrated challenge spanning ecology, production, and governance.

Oil palm is not an ordinary cultivated crop that relies only on natural rainfall; rather, it is a tropical agricultural production system with extremely high hydrological sensitivity. Over the past 30 years, the rapid expansion of global oil palm cultivation has profoundly reshaped regional hydrological patterns in multiple major producer countries. Olukanni et al. (2024) identified five core themes for oil palm hydrological research, including infiltration dynamics; Ajadi et al. (2025) pointed out that global demand for palm products continues to increase, making it essential to manage water-related impacts to adapt to climate stress. Verchius et al. (2025) verified that both water surplus and water deficit can undermine four core production indicators, which further confirms the necessity of research in this field.

Combining Pauzi et al.'s (2025) cross-regional analysis of oil palm plantations covering Southeast Asia, West Africa, and Latin America, and Raketh et al.'s (2024) study on soil moisture during drought periods, this study proposes that the hydrology of oil palm plantations is shaped by three core groups of factors: soil oversaturation in humid regions and water scarcity in arid regions, and climate variability. inhibit plant vigor and reduce fruit bunch yield respectively. Therefore, integrated, adapted solutions must be implemented, and single, isolated technical interventions should be avoided.

Emerging climate projections have further exacerbated water governance challenges in oil palm plantation landscapes. A study by Yew et al. (2020) confirms that current trends of rising extreme rainfall intensity, as well as longer and more frequent dry seasons, have introduced entirely new uncertainties to water management planning and plantation yield forecasting. At the natural systems level, three categories of measures must be implemented: hydrological monitoring, adaptive drainage, and soil water retention. Under the sustainability framework, the goals are reduced to nutrient loss, protecting riparian zones, and limiting sediment transport. Climate variability is the core driver of adaptive water management, rather than a peripheral consideration.

After reviewing existing research, this review found that studies related to water resource management in oil palm plantations have expanded continuously. However, current literature is scattered across six major disciplines including hydrology and agronomy, with clear divides in their core research priorities: some studies focus on drainage technology, other prioritize drainage efficiency, and still others center on water retention and soil conservation. These divides limit the ability of researchers, plantation managers, and policy stakeholders to identify and adopt appropriate water management strategies.

Water resources hold core strategic value for agricultural systems, as they underpin ecological performance, crop yields, and the long-term resilience of plantations. As a crop with high water demand, oil palm's production capacity depends heavily on stable hydrological conditions, which makes water management particularly critical. Currently, core gaps persist in the existing body of water-related research focused on oil palm landscapes: the interactive relationships among four categories of factors—technical interventions, adaptive governance, climate response capacity, and implementation constraints—have not yet been FULLY clarified. This study is a literature review on water resource management in oil palm plantations. Its primary objectives are to fill these research gaps. It will integrate evidence from four categories of academic sources: hydrological simulation, field assessment, water quality research, and agronomic evaluation. It will address five core research tasks: outlining the field's development trajectory, identifying commonalities across cultivation scenarios, validating evidence-based management strategies, comparing regional water condition challenges, and proposing practical measures adapted to diverse contexts by leveraging the interdisciplinary intersection of water quality and agronomy.

Literature Review

1. Conceptual and Theoretical Foundations of Adaptive Water Governance in Agricultural Landscapes

Water resources management is a core pillar of sustainable agricultural systems, and a critical foundation for analyzing water resources governance in agriculture-dominated landscapes. Ferreira et al. (2023) proposed that hydrological variables cannot be analyzed in isolation within tropical agricultural water systems, and that the interactions among four categories of factors must be managed and considered as an integrated whole. This review takes this claim as its conceptual basis and analyzes oil palm water resources management from the perspective of adaptive governance.

Water resource management for perennial crop systems such as oil palm involves engineering infrastructure, hydrological assessment, and agronomic decision-making. Nobilly et al. (2022) pointed out that drainage networks, irrigation facilities, and plantation terrain jointly determine the long-term hydrological performance of large-scale plantations. As climate variability increases, static water management is increasingly being replaced by adaptive approaches that emphasize risk reduction, efficiency improvement, and resilience building. Such approaches require assessment not only of technical performance, but also of governance suitability and implementation capacity. Akanwa and Joe-Ikechebelu (2021) proposed that water resources have ecological, agronomic, and infrastructure-related attributes. Therefore, effective intervention depends on the alignment of field hydrology, plantation engineering, and watershed governance within a coordinated multi-level framework.

Recent literature also supports this integrated view of hydrological governance. Adaptive water governance approaches emphasize stakeholder participation, decentralized institutional arrangements, environmental monitoring, and cross-sector coordination. In plantation and wetland contexts, community-based governance and stronger institutional capacity have been associated with improved conservation planning and reduced ecological risks linked to land-use expansion (Indriyana et al., 2026; Tua et al., 2025). Building on the conclusions of previous research, this review proposes that the hydrological sustainability of oil palm landscapes is not determined solely by field-level technical measures; it also depends on the institutional conditions that govern the implementation of water resource.

2. Hydrological Responses to Land-Use Change in Oil Palm Regions

A large body of existing literature, including meta-analyses and landscape-scale studies, focuses on the hydrological effects of converting primary forest land or agroforestry systems to oil palm plantations. This type of land conversion alters four core hydrological processes. Asmadi and Tamunaidu (2023) note that these impacts vary across five site factors, and that generalized assumptions must be abandoned, while site-specific interpretations should be adopted instead.

Existing watershed hydrology research shows that young artificial forests have higher water yield and lower infiltration capacity than primary forests, and that the cumulative biomass of primary forests can improve soil structure and organic matter content (Jijingi et al., 2025). Studies on peatland hydrology point out that water level regulation is key to maintaining peat stability, while stand age and soil type regulate hydrological outputs. Drawing on these findings, this study proposes that the hydrological consequences of oil palm expansion must be interpreted by integrating spatio-temporal context, land use history, and management intensity.

A study by Sutiarso et al. (2022) found that landscape assemblages composed of four types of land parcels, including plantations and riparian buffer strips, exert a far stronger influence on watershed water flow than any single land cover type, thereby overcoming the parcel-scale limitation of traditional hydrological research. The hydrological response to oil palm expansion is shaped by the interaction between biophysical conditions and management measures, and water management strategies must be compared across five core dimensions.

Riparian buffers at the watershed scale fulfill core ecohydrological functions by reducing sediment transport, limiting nutrient loss, and supporting freshwater biodiversity, a finding corroborated by Giam et al. (2015). A hydrological modeling study by Asmara and Randhir (2024), points out that these buffers can mitigate disturbances to runoff and nutrient flows caused by the conversion of forests to oil palm plantations. This review maintains that water resource management for oil palm operations must incorporate dual-scale assessments covering both the plantation and watershed scales.

3. Soil–Water Interactions and Their Implications for Plantation Management

Soil-hydrological dynamics in the context of plantation forests is a core research theme in forestry and agricultural hydrology. The ability of soil to retain water, support nutrient cycling, and promote root development determines how effectively plantation forests can cope with rainfall fluctuations and seasonal drought. The interaction among soil texture, compaction, organic matter, and conservation-oriented management acts as the core link between hydrological regulation and agronomic production.

A study by Novita et al. (2024) points out that three strategies consisting of legume cover crops, root-zone plastic mulching, and crop residue retention can improve soil infiltration rates, reduce erosion, and stabilize microclimate humidity. This conclusion provides the core basis for this review to identify the hydrological resilience supporting mechanisms of soil and water conservation measures in oil palm plantations. Existing studies have confirmed that planting Asystasia gangetica within oil palm cultivation systems can enhance the water-holding and infiltration capacity of the rhizosphere, maintain water supply during dry periods, and reduce surface runoff and soil erosion on sloping land. When paired with measures such as terraces and contour planting adapted for undulating terrain, this approach can regulate soil-water relationships, and balance both plantation productivity and hydrological stability.

Mulching and crop residue retention can improve soil physical properties, enhance water holding capacity and water redistribution, and strengthen water management. Mulching with empty fruit bunches is particularly important, as it can promote the accumulation of soil aggregates and organic matter and improve the water storage capacity of the entire soil layer. The retention of pruned fronds, empty fruit bunches, and other organic residues also supports nutrient cycling processes that indirectly improve water-holding capacity and long-term productivity (Moradi et al., 2015; Tao et al., 2016; Wijayani et al., 2022). This evidence indicates that residue-based management contributes not only to short-term moisture regulation, but also to broader ecosystem functioning in plantation landscapes.

Fidan et al. (2025) note that artificial forests located in heavy-texture areas and regions with periodic waterlogging require the installation of surface drainage systems to prevent anaerobic conditions from impeding root respiration and nutrient absorption. This paper proposes adaptive, context-matching measures for regions with long dry seasons, namely selective irrigation, soil moisture monitoring, and adjustments to water scheduling plans. This research finds that the water management priority for the same plantation crop is determined by its dominant stressors, including waterlogging, water shortage, and seasonal precipitation variability. The study opposes the use of an inflexible, one-size-fits-all management scheme, and emphasizes that soil-water interactions serve as a practical decision-making guide for managers to align water governance plans with the biophysical conditions of a given site. Any universal scheme must be adapted to local soil properties, slope positions, rainfall characteristics, and management capacities.

4. Engineering and Technological Approaches to Plantation Water Governance

In addition to ecological approaches, engineering studies have examined the technical mechanisms of water regulation in plantation systems. Ashraf et al. (2019) focus on drainage systems consisting of main drainage ditches, collection ditches, field ditches, and integrated slices, particularly in lowland and peat-based plantations. This system can drain accumulated water, maintain a suitable groundwater level, ensure soil aeration, and prevent crop waterlogging, but it must balance four major constraints: downstream flood risk, peat subsidence, water scarcity in the dry season, and operation and maintenance cost.

In recent years, the core goal of hydrological management for planted forests has been to strengthen hydrological resilience. A study by Tan and Lim (2019) shows that three types of digital technologies can achieve real-time monitoring of hydrological indicators, supporting precise management, optimized input, and reduced risk. The technologies also tend to improve the timeliness and accountability of decisions related to drainage suspension, irrigation scheduling, and flood response. Under rapidly changing climate conditions, adaptive water infrastructure is needed to respond to fluctuating rainfall, extreme events, and seasonal variability. Retention ponds, adjustable weirs, controlled drainage systems, early-warning dashboards, and GIS-based monitoring tools represent practical options for improving field-level responsiveness. However, promoting these solutions among smallholder farmers faces four categories of constraints including limited funding, technical capacity, maintenance reliability, and institutional support. Therefore, technological innovation should serve as a complement to ecological and governance measures, rather than a substitute for them.

In oil palm plantation systems established on peatland substrates, drainage management is a core priority. Excessive drainage can trigger three categories of environmental hazards; at the regional scale, appropriate hydrological conditions can be maintained through sluice gate systems and groundwater level regulation. Imanudin et al. (2021) and Febrianti et al. (2026) reported that this approach reduces degradation risk. At the field level, conclusions from Tarigan et al. (2016) show that leaf pile arrangements and sediment basin treatments can cut runoff by up to 31% and optimize the flow convergence function of the watershed. To support adaptive management, current groundwater regulation is increasingly supported on multiple categories of supporting tools. Technical tools include remote sensing, the SWAT and SIMGRO hydrological models, and field observations. According to Febrianti et al. (2026) and Wösten et al. (2006), these tools can assess groundwater dynamics, predict hydrological impacts, and design risk mitigation strategies. Policy-focused tools integrate groundwater extraction into plantation water allocation frameworks. Brookes et al., (2017) noted that these tools can safeguard ecological functions and alleviate stress on wetlands.

5. Occupational, Institutional, and Governance Perspectives

This paper reviews existing research and finds that studies on water resources management have expanded beyond the traditional scope of biophysical and engineering analysis, and have integrated the perspectives of institutions, regulation, and governance. It further draws on Johan and Chan (2020), who argue that plantation water governance is shaped by regulation and technology, and that the core of its effectiveness depends on the effective implementation of governance mechanisms in field practices.

Studies by Culman et al. (2019) and Mustafa et al. (2025) show that multi-stakeholder collaboration with participation from governments, plantation enterprises, smallholder farmers, and community organizations can align the water use interests of upstream and downstream areas within a river basin, reduce conflicts, and is more suited to river basin scenarios where cross-boundary impacts affect downstream regions than the traditional command-and-control model. Current mainstream water resources management certification systems and sustainability reports can advance water resource governance and protection through three pathways: documentary recording, continuous improvement, and transparent assessment. However, their effectiveness is constrained by four core factors, including audit quality and data availability. This study proposes that water resource governance and protection in oil palm landscapes should be treated as a socio-technical system, whose hydrological outcomes are shaped jointly by three types of mechanisms: regulatory, voluntary, and collaborative.

Climate-responsive water management expands the perspective of traditional water governance. A study by Delgado et al. (2024) found that irrigation regimes that matched evapotranspiration demands and adapt to seasonal water use needs can improve water use efficiency and stabilize oil palm output under climate change. Ismail et al. (2024) proposed that remote sensing and GIS can accurately monitor soil moisture and vegetation conditions to support refined water management, and that adaptive water governance must rely on both institutional coordination and reliable access to hydrological information.

6. Best Practices Across Regions: Toward A Comparative Synthesis

Dearlove et al. (2024) systematically identified four repeatedly validated best practices for water resource management in oil palm cultivation landscapes: landscape-adaptive drainage design, vegetation buffer strips along waterways, adaptive soil protection techniques, and moisture monitoring technologies. The efficacy of these practices varies according to local conditions and cannot be directly adopted across different regions.

Water resource management that enhances hydrological resilience in plantations requires the implementation of three general hydrological operation and maintenance measures: regular drainage maintenance, sediment control, and vegetation management. These measures sustain runoff efficiency and prevent blockages in drainage infrastructure during peak rainfall periods. For areas with vulnerable soil conditions, De Oliveira et al. (2022) proposed that groundwater-level regulation technologies should be adopted to balance production benefits and soil stability. The long-term performance of infrastructure depends not only on its initial design, but also on routine operation and maintenance, monitoring, and the capacity to adjust to climate change. Existing comparative studies have confirmed that multi-dimensional coordinated practices are far superior to isolated intervention models. Strategies that integrate structural measures, vegetation protection, monitoring tools, and governance coordination can help plantations manage hydrological variability and improve overall resilience.

Studies by Rajoo et al. (2022) and Shukla et al. (2021) further demonstrate that regular drainage maintenance, sediment control, and vegetation management sustain flow capacity, reduce erosion, and prevent infrastructure blockages during peak rainfall periods. For areas with vulnerable soil conditions, de Oliveira et al. (2022) proposed that groundwater-level regulation technologies should be adopted to balance production benefits and soil stability. Four types of structural soil and water conservation measures—contour ditches, silt pits, terraces, and water retention ditches—can reduce runoff and sediment yield. Integrated schemes that combine engineering and vegetation measures deliver the optimal erosion reduction effect, and Wang et al. (2026) and Lu et al. (2024) reported that the maximum erosion reduction rate reached 85%. Studies by Shukla et al. (2021), Judijanto and Nurhayati (2026), Rajoo et al. (2022), and Sukmawan et al. (2026) collectively confirm that integrated soil and water conservation management can improve soil infiltration, boost water storage, reduce inundation risk, and maintain watershed stability. However, its effectiveness is highly dependent on four core conditions: soil characteristics, topography, rainfall intensity, and maintenance quality.

Existing literature in the field of water resources management has identified three generation pathways for best practices. The core characteristic of these practices is context specificity: they can only be effectively implemented across different scenarios if they are integrated with the actual local conditions of a region. This review identifies four key research gaps in the field of hydrology and water resources: (1) the lack of synthesized comparative evidence for best practices across ecological scenarios; (2) insufficient interdisciplinary integration of environmental, engineering, and governance research; (3) the failure to fully incorporate climate variability into operational long-term water resources management models; (4) practical factors including maintenance capacity, smallholder resources, data access, and governance constraints. This review adopts an integrated water resources governance perspective, synthesizes multidisciplinary evidence to fill these gaps, and supports future research, policy formulation, and plantation water management.

This study draws on the findings of Nasution et al. and Tanika et al. (2024) and proposes that the optimal solution for the hydrological sustainability of oil palm landscapes is a holistic adaptive framework that integrates governance and conservation. This framework is implemented through the protection of high conservation value areas and rolling out participatory socio-hydrological tools, enabling it to balance production and ecological resilience while addressing climate and hydrological uncertainties.

Methodology

1. Review Design

This study adopts systematic literature review methods to examine water resource management in oil palm plantations. This method can effectively outline the full scope of the research objective aimed at the study. The study also strictly follows the PRISMA protocol, a universal standard for systematic review, to ensure that the entire process of literature identification, screening, evaluation, and inclusion is transparent, valid, and replicable. Current research in this field is scattered across academic disciplines covering environmental science, agricultural engineering, and plantation management, and consisted primarily of separate studies focused on individual dimensions, which prevents the formation of an integrated understanding of the topic. This study will synthesize existing evidence, extract common patterns, and fill this gap in the field.

2. Search Strategy and Database Selection

This study conducts a systematic review focused on water resource management in oil palm plantations. Literature screening strictly follows the four-stage framework of the PRISMA guidelines, and the steps of literature identification, initial screening, eligibility assessment, and final inclusion were completed in sequence, and the entire workflow can be seen in Figure 1. To ensure full coverage of relevant academic disciplines, this study selected the Scopus database as the primary source of literature. The review conducted a search using the main string "water resource management" AND "oil palm plantation" and ultimately gathered 281 publications from the Scopus database. This database covers all four core research fields of this study.

To refine thematic focus and restrict the search to water-related operational and sustainability issues within plantation contexts, the query was expanded using the Boolean structure: *("oil palm" OR "oil palm plantation" OR "palm oil cultivation" OR "palm oil industry") AND ("water" OR "water management" OR "water resources" OR hydrology OR "water use") AND ("practices" OR "management practices" OR "sustainable practices" OR "best practices" OR "management strategies") AND (issues OR challenges OR impacts OR "environmental impacts" OR "water-related")*. This extended Boolean search string was used to refine the thematic scope of the review. After excluding 184 ineligible records, 97 records were retained for the next screening stage. The literature included covers seven core thematic categories, and comprehensive documentations of all review procedures ensure the reproducibility of this study.

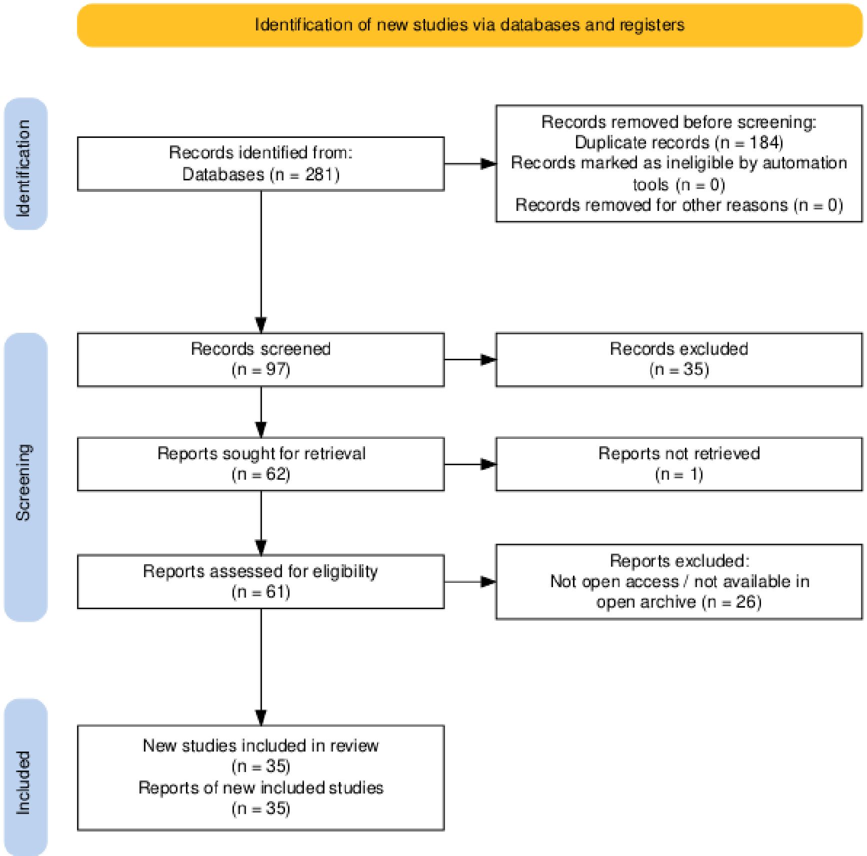

Fig 1. Systematic literature review process based on the PRISMA protocol

3. Inclusion and Exclusion Criteria

This study focuses on water resources management in oil palm plantations, and adopts the systematic literature review method, which is appropriate for this research. The full process of literature management and review follows the PRISMA workflow from start to finish, ensuring that the study is rigorous and replicable. Existing research in this field is scattered across four mainstream disciplines and is largely conducted within isolated research dimensions, limiting the development of an integrated understanding. This study synthesizes existing evidence, identifies common patterns, and addresses this research gap. This study conducted literature screening through three rounds, successively excluding works that fell outside the 2019–2025-time window, were not published in English, or lacked eligible full-text access. A final set of 35 peer-reviewed studies was retained to ensure the transparency, focus, and replicability of this review.

4. Screening Procedure and Bias Control

The literature screening process developed for this study centers on two core objectives: enhancing the transparency of academic research and reducing literature selection bias. The entire process is implemented in three successive stages. First, the titles and abstracts of all initially identified literature are reviewed to eliminate irrelevant entries. Second, the remaining studies are evaluated against pre-defined inclusion and exclusion criteria. Third, the full-text verification is conducted, and only valid literature aligned with the scope of oil palm water resource management is retained. This study conducts a literature review centered on the topic of oil palm water use. During the initial screening stage, all studies with uncertain inclusion eligibility are retained for full-text re-review. This approach not only avoids the risk of omitting interdisciplinary research but also ensures that all studies ultimately included meet the requirements of being relevant to the research topic and having uniform methods.

5. Quality Appraisal of Included Studies

The research independently developed a dedicated literature quality assessment process for this thematic review focused on oil palm water resources management. This process covers three core assessment attributes for evaluating all included studies: topic relevance, clarity of research design, and practical value of the findings. To guarantee the consistency of all assessments, this research developed a structured verification checklist. Given that the included studies differed substantially in terms of study design and scale, the study discarded strict methodological exclusion criteria and instead adopted thematic contribution as the primary assessment criterion. This approach enables the incorporation of diverse forms of evidence, while also allowing the reviewers to identify methodological variations and potential biases.

6. Data Extraction and Thematic Coding

This study constructed a structured data extraction framework to integrate and organize the information obtained from the 35 target studies included in the analysis. The framework established 10 extraction dimensions that cover core elements such as literature metadata, study location, research design, cultivation scenarios, and hydrological variables followed by iterative thematic coding work in subsequent research stages was carried out. The study first clustered the included relevant studies into nine themes, including hydrological change and other related topics. It later adjusted this classification after distinct research patterns emerged, to reduce theme overlap, improve the accuracy of interpretations, and ensure that the analytical procedures were traceable and reproducible.

7. Reference Management and Synthesis Procedure

This study is a systematic literature review focused on water-related issues in oil palm plantations. It uses Mendeley Desktop for literature management, and its entire research workflow is transparently archived. This study did not conduct three types of primary research: original data collection, field observation, and focus group discussions. All analyses were completed solely based on secondary academic literature. Due to the high level of heterogeneity among the studies included in this research; the study did not adopt a meta-analysis. Instead, it adopted a qualitative interpretive synthesis approach to carry out an integrated analysis across three core dimensions: technology, ecology, and management. This work aims to provide support for existing practices and future research in this field.

8. Methodological Scope and Limitations

This study included only studies indexed in Scopus that are English-language, open access, or openly archived. This threshold improves the reproducibility of this review and the full-text verifiability of included research, but it may also omit relevant studies from other sources. The 35 studies ultimately included form a transparent and reproducible collection of recently available literature, and this set is by no means an exhaustive compilation of all evidence in the field. When future cross-dimensional comparative studies interpret their own findings, this limitation should be considered.

Results

This study screened literature in accordance with the PRISMA protocol and included 35 peer-reviewed studies focused on water resource management in oil palm plantations, published between 2019 and 2025. The review identified eight interconnected core analytical theme clusters. These theme clusters serve as analytical categories, rather than independent, mutually exclusive research directions, as most of the included studies simultaneously cover multiple dimensions such as hydrology, agronomy, and governance. This classification provides a clear analytical framework for in-depth analysis of each theme in subsequent research: (1) Hydrological Alterations Linked to Plantation Development, (2) Water-Use Efficiency and Irrigation Needs, (3) Drainage System Performance and Flood Mitigation, (4) Groundwater Dynamics and Water-Table Regulation, (5) Nutrient Leaching and Water-Quality Considerations, (6) Soil–Water Interactions and Evapotranspiration Patterns, (7) Water-Related Environmental Risks Under Climate Variability, and (8) Best-Practice Measures in Contemporary Plantation Management.

This study conducts thematic distribution analysis of literature on oil palm landscapes to calculate the occurrence proportions of eight analytical themes. Hydrological alteration accounts for the largest share (80% of studies), followed by drainage system performance (71%), soil–water interactions and evapotranspiration (63%), water-use efficiency and irrigation (57%), groundwater dynamics (51%), water-quality and nutrient leaching (46%), climate-related risks (40%), and best-practice measures (37%). These percentages represent the relative frequency of theme occurrence and cannot be interpreted as effect sizes or evidence of technical effectiveness. Among the included studies in this review, 68% cover multiple research topics, a finding that confirms the inherent intrinsic interconnections among hydrological processes, agronomic management, and environmental conditions.

The aim of this study is to identify the distribution characteristics and underlying patterns of literature in the field of plantation hydrology. Research in this field falls into two categories: the dominant body of research on hydrology and drainage, and the equally prominent body of research on soil-water interactions and evapotranspiration, which focus respectively on the shaping of watershed hydrology and the regulation of micro-hydrological. This study reviews academic literature on water fields and presents the following findings: Research on groundwater and water quality only receives moderate attention, represents a relatively small proportion of the literature, and is constrained by two key limitations: strong site-specificity and the requirement for long-term monitoring. The emerging research clusters focused on climate risk and best practices can support adaptive management amid shifting rainfall patterns. The current literature system, however, suffers from a clear imbalance: the capacity to record hydrological processes far exceeds the capacity to assess management interventions.

Current academic literature in the fields of hydrology and water management has developed many mature, well-established research areas. This paper reviews existing research in the field, identifies four gaps that remain to be expanded to advance integrated research directions. Subsequent chapters will conduct core analysis following a pre-set framework. This review establishes consistent and transparent data interpretation standards for all included studies, to clarify analytical boundaries and ensure the rigor and reliability of the analysis.

1. Hydrological Alterations Linked to Plantation Expansion

Studies included in this hydrological review show that hydrological alteration is the theme with the highest consistency of supporting evidence, and that the conversion of primary forests or mixed agricultural land to oil palm plantations alter three types of hydrological processes: infiltration, runoff, and water distribution (Ahmed et al., 2024). A study by Wandri et al. (2025) focusing on oil palm plantations confirmed that after this land conversion, canopy interception decreases, throughfall increases, and soil water recharge patterns during peak rainfall periods change; Anyaoha and Zhang (2023) found that in regions with annual rainfall exceeding 2,000 mm, the infiltration changes triggered by this land conversion are correlated with four factors including litter depth. Abdullah and Hussein (2020) found that peak flow rates are higher in the early stage of development but gradually stabilize as root systems mature and soil structure improves. This review emphasizes that these conclusions, drawn from different landscapes and based on distinct simulation assumptions, can only serve as evidence of general hydrological changes, and cannot be used as universally transferable quantitative estimates. Hydrological responses at the watershed scale exhibit significant heterogeneity. Popkin et al. (2022) confirmed that well-managed oil palm plantations with adequate riparian buffers can maintain stable baseflow. Rathore et al. (2019) found that the absence of riparian buffers exacerbates fluctuations in flow regimes, and this effect is especially pronounced in high-intensity rainfall areas. These differences highlight the sensitivity of hydrological systems to site-level management, meaning that multi-dimensional parameters must be considered to support hydrological zoning, riparian protection, and drainage planning.

2. Water-Use Efficiency and Plantation Irrigation Needs

The long-held public perception that oil palm is a crop fully dependent on rainfed cultivation is inaccurate. Currently, research on supplemental irrigation for oil palms in water-deficient areas has gained increasing attention. Aziz et al. (2024) found that the water consumption of mature oil palms fluctuates in line with humidity, soil type, tree age, and seasonal evapotranspiration demands. Settapong et al. (2025) proposed that long-term drought in drought-prone regions leaves soil water storage unable to support fruit bunch development, which in turn causes yield losses. This paper argues that the irrigation requirements of oil palms exhibit heterogeneity, with key determinants including rainfall seasonality, soil water-holding capacity, and the age of trees.

The current development of high-efficiency agricultural irrigation technology faces both opportunities and bottlenecks. A number of existing studies have outlined the value of different technical pathways: a study by Tapia and Samsatli (2020) found that precision irrigation integrated with soil moisture sensors and remote sensing models improves efficiency by nearly 22% compared with traditional irrigation; Purnama et al. (2025) proposed that drip irrigation can reduce water resource loss, while by Najihah et al. (2020) pointed out that integrated water and fertilizer technology can optimize the matching between water supply and nutrient absorption. The large-scale implementation of such technologies generally encounters the same set of common constraints: Capital costs, technical capacity, energy availability, and adaptability to planting scenarios of all sizes.

3. Drainage Infrastructure and Flood-Control Performance

The drainage systems of oil palm plantations are a key component of water resource management and play a critical role in high-rainfall regions or peatland landscapes. Gómez et al. (2023) confirmed that traditional drainage canals, whose parameters such as spacing and depth are adapted to local hydrology, can reduce waterlogging. Abdullah and Hussein (2021) proposed that controlled drainage systems equipped with adjustable weirs can reduce flood risk in specific areas during periods of high rainfall. However, this system has site-specific limitations. To scale up their application, two covariates, namely rainfall intensity and soil permeability, must be integrated.

Existing research in the field of hydrological management for artificial plantations generally centers on two core challenges: Haque et al. (2022) found that sediment accumulation in the main canals of aging plantations drives up maintenance needs and reduces water transport efficiency; Vargas-Carpintero et al. (2021) pointed out that newly built plantations on mineral soils suffer from excessively fast storm runoff and insufficient watershed coordination, which easily triggers downstream flood peaks. Abogunrin-Olafisoye et al. (2024) proposed that a composite system integrating layered drainage, grit chambers, and vegetative filter strips can effectively regulate runoff and reduce sediment transport. Before this technology is put into practical application, a full-chain performance assessment covering five core dimensions including drainage speed and soil protection must be completed.

4. Groundwater Dynamics and Water Table Regulation

Groundwater level is a core factor determining palm health, nutrient use efficiency, and soil stability (Nasrolahi et al., 2025). Marini et al. (2024) proposed that the optimal groundwater level must be adapted to local conditions, and there are differences in the applicable standards for mineral soils and peat soils. Abubakar et al. (2021) verified that controllable water level management implemented through weirs and water baffles can only stabilize fluctuations and alleviate stress when active monitoring and adjustment are carried out. This paper puts forward that an elastic management interval should be set, which is affected by four core factors including soil type.

Published hydrological simulation studies by Siallagan et al. (2025) and Susanti et al. (2021) show that groundwater level drawdown caused by adjacent land uses and extraction from non-agricultural deep wells both impact the groundwater levels of artificial forests, with the degree of influence constrained by conditions including soil hydraulic conductivity and hydrogeology; most studies in the field hold that properly managed artificial forests can maintain stable groundwater levels. Based on this consensus, this paper proposes that groundwater level monitoring should be carried out outside forest boundaries, a measure that is particularly applicable to regions where estate drainage, smallholder farm plots, community water use, and non-agricultural extraction all belong to the same hydrological system.

5. Nutrient Leaching and Water Quality Considerations

Agricultural water quality is an important research topic that has been repeatedly discussed in academic circles, with its two core concerns being nutrient leaching and sediment deposition. Relevant analyses can be conducted based on two existing studies: Munévar-Martínez's et al. (2025) study on nitrogen leaching in intensive young palm plantations, and the study by Anggat et al. (2024) on phosphorus adsorption in tropical mineral soils. The dynamics of these processes are influenced by five categories of variables: fertilization timing, rainfall events, soil chemical properties, sampling frequency, and drainage connectivity. Researchers must remain alert to the risks of inappropriate cross-study comparisons.

Ishak et al. (2021) found that sediment loads in surface runoff increase significantly under intense rainfall events and on steep slopes; Lekete et al. (2019) showed that sediment loads in plantations with year-round vegetative ground cover are lower than those in bare-land management systems; Maulina et al. (2025) noted that the biochemical oxygen demand of plantation drainage is mostly discussed in relation to local regulatory thresholds and the sensitivity of downstream water quality. The synthesis presented in this paper finds that water quality outcomes are generally correlated with soil conservation measures and fertilization timing, and current research evidence in the water quality field is far less integrated than that in the drainage and hydrology fields. Long-term monitoring that links nutrient management, sediment control, and impacts on downstream aquatic ecosystems is urgently needed.

6. Soil–Water Interactions and Evapotranspiration Patterns

The three soil properties—soil texture, organic matter content, and bulk density—exert a strong driving effect on soil water retention and evapotranspiration patterns. According to reviews by Febria et al. (2021) and Zamri et al. (2025), the difference in water-holding capacity between mineral soils and peat soils stems from variations in organic matter, porosity, and drainage conditions. Post-drainage subsidence of peat soils will alter their interactions with the groundwater table. This paper proposes that soil is far from a static background and instead acts as a core variable that shapes the effectiveness of field water management. Oil palm evapotranspiration exhibits significant seasonal differences. Zaitunah et al. (2025) found that its measured evapotranspiration values fluctuate across three types of time periods, and its annual estimated values are constrained by two categories of factors; Teow et al. (2021) pointed out that mature oil palm stands have lower soil evaporation than young stands, due to their dense shading and abundant litter. Meiryani et al. (2022) reported that the evapotranspiration rate of well-managed oil palm plantations can approach that of some secondary forests. This study identified four core ecological differences between the two systems, including those related to canopy structure and root distribution, and comparative research across these two types of systems must be advanced with caution.

7. Water-Related Environmental Risks Under Climate Variability

The existing literature reviewed in this study consistently shows that the volatility of rainfall intensity and distribution across the world's major oil palm producing regions has kept rising. Shehu et al. (2019) pointed out that bounded by emission scenarios and model assumptions, Southeast Asia will experience a trend of increased rainfall in the wet season and decreased rainfall in the dry season. This trend will intensify the risks of short-term water shortages and flooding in months with peak rainfall, eroding the reliability of traditional irrigation and drainage designs that rely on the assumption of stable rainfall.

Substantial body research on drought stress in oil palms has accumulated to date. A 2021 long-term assessment by Ahmed et al. (2021) showed that when monthly rainfall during El Niño-induced drought periods falls far below normal levels, oil palm yield exhibits clear vulnerability. More recently, Bayona-Rodríguez and Romero (2024) noted that extreme rainfall triggers three risks across some planting estates: flooding, erosion, and inadequate drainage capacity. It is necessary to develop adaptive water management strategies that address both drought and flood risks. While current research on hydrological modification, drainage, and related topics is well-established, research on climate risks lags far behind, making it urgent to integrate three dimensions to advance research in this field.

8. Best-Practice Measures in Contemporary Plantation Management

Plantation projects with sound operational performance share one common feature: they adopt multi-layered water resource management strategies. The first type of strategy is an integrated drainage system equipped with controllable weirs, sedimentation tanks, and vegetation strips. Nupueng et al. (2023) confirmed that such water resources regulation systes can regulate runoff peaks and manage groundwater levels; while the empty fruit bunch mulching method, verified by Darras et al., (2019) can improve soil water retention in the dry season and reduce evaporation. These findings suggest that water resources management must combine multiple measures and must not rely on a single intervention.

Riparian buffer zones are a widely documented water management measure for agricultural watersheds in academic research. Payán and Boron (2019) pointed out that 10–30-meter-wide buffer zones can only fulfill their functions of reducing sediment deposition, stabilizing stream banks, and regulating hydrology if their width and vegetation structure are adjusted to suit local stream conditions and slope gradients. Precision agronomic practices such as precision fertilization and the use of slow-release fertilizers can help smallholder farmers and plantation operators reduce nutrient leaching and improve water quality. Field practices show that water management requires localized monitoring rather than uniform, one-size-fits-all interventions, and existing reviews lack comparative evidence from remote, under-infrastructure regions that cover all four core dimensions.

This review synthesizes existing research in the field of water resources management for oil palm plantations. It clarifies that the complex interaction between site-specific biophysical conditions, climate variability, and management strategies is the core shaping factor. Drawing on eight major themes extracted from the 35 studies included in this review, the interplay of these themes jointly influences the effectiveness of water governance in oil palm landscapes. The body of pre-existing research evidence synthesized in this review can support subsequent analyses of the water resource management performance of oil palm plantations and identify areas for future optimization of related practices. Due to variations across past studies in their design, scale, indicators, and regional contexts, the outcomes of this work constitute only a thematic synthesis rather than a standardized quantitative assessment. For relevant governance initiatives, core strategies must center on integration, contextual adaptation, and adaptive management, supported by complementary enablers including monitoring, operation and maintenance, and cross-stakeholder coordination at the catchment level.

Discussion

Existing systematic literature reviews in the field have included 35 eligible studies and proposed that water resource management in modern oil palm plantations has shifted to a multi-dimensional model that integrates three types of tools to address water-related challenges. Building on this foundation, this study focuses on the following research question: How under diverse biophysical and climatic conditions can water management strategies for oil palm plantations mitigate hydrological challenges and improve water governance performance? To address this question, it is necessary to analyze five interacting variables: plantation hydrology, engineering design, climate variability, governance capacity, and implementation constraints. Existing literature puts forward that plantation governance has shifted from passive response to customized structured governance, and its effectiveness shows heterogeneity across different geographic regions and operation scales. This paper addresses this research gap by synthesizing current evidence on adaptive water resource management in oil palm plantations.

This paper synthesizes the academic consensus in the field of hydrological management for mature planted forests. The global hydrological management sector is currently undergoing a paradigm shift, moving away from the traditional old model centered on drainage to a new balanced management paradigm that integrates water retention, soil moisture maintenance, and controlled discharge. This study takes mature artificial forest plantations as its core research setting. Drawing on the findings of Anwar (2019) and Turjaman et al. (2024), this paper notes that these forest plantations, affected by terrain, soil texture, and rainfall patterns, face the problems of waterlogging and sudden runoff surges. The hydrological heterogeneity of plantations expanded into multi-terrain regions has become increasingly prominent, requiring customized management tailored to the conditions of small watersheds. Abubakar et al. (2024) confirmed that systems balancing natural drainage and the water demand of oil palm roots deliver superior performance. This paper argues that the unitary drainage logic should be abandoned, and evaluation frameworks must be restructured to integrate whole-basin hydrological management, to balance the four core goals of farmland productivity, flood peak regulation, soil conservation, and protection of downstream water environments.

A broad consensus across published literature in the hydrology field shows that the hydrological challenges of mineral soil landscapes differ significantly from those of peat-dominated landscapes. This paper focuses on plantations located on medium-to-steep slopes with mineral soil, whose core hydrological risks are surface runoff, erosion, and uneven infiltration. Existing management measures for these risks include terraces, contour ridges, grassed waterways, and sediment retention structures. Putra et al. (2021) confirmed that these measures can stabilize flow paths, reduce sediment displacement during heavy storm events, and lower sediment accumulation and nutrient loads in downstream waterways. Subramaniam and Hashim (2018) pointed out that pairing these measures with vegetative ground cover and organic amendments can further improve their effectiveness. However, existing research has not adequately covered the costs, labor requirements, maintenance frequency, and long-term performance of these measures, with a particular lack of relevant evidence from smallholder farms and remote plantations.

The hydrological management agenda of oil palm plantations on peatlands is fundamentally different from that of other land use scenarios. Its core priority goal is to maintain a stable groundwater level, to reduce peat oxidation, slow land subsidence, and lower the risk of dry-season wildfires. The plantations rely on three types of infrastructure to balance the demand for peat water retention and oxygen supply for palm roots: adjustable weirs, canal interception facilities, and controllable drainage systems. The rationality of this regulatory approach has been confirmed by Córdoba et al. (2019). When paired with precision regulation supported by monitoring wells, water level gauges, and automatic recorders, Lalruatkimi et al. (2025) further demonstrated that this management model can adapt to variable climates and reduce hydrological fluctuations. However, water level management faces a core trade-off: excessive drainage will exacerbate subsidence and wildfire risk, while excessive water storage will impair root oxygen supply and field accessibility. Therefore, dynamic monitoring rather than a fixed drainage scheme must be adopted.

In existing academic literature, the importance of strategies to improve water use efficiency in the agricultural planting sector has become increasingly prominent. Octifanny et al. (2025) sorted out five categories of water-saving measures commonly used in artificial plantations: soil moisture sensors, deficit irrigation technology, micro-irrigation systems, mulching to retain soil moisture, and returning organic matter to farmland. Nadzim et al. (2025) confirmed that irrigation scheduling based on real-time moisture data can optimize water resource allocation without negatively affecting crop yields. However, most existing studies lean heavily toward technical dimensions, lacking analysis from socioeconomic perspectives, and also face core constraints including investment capacity, water rights regulation, energy accessibility, personnel training, and whether yield gains can cover the costs of installation, operation and maintenance.

In hydrologically active plantation areas characterized by heavy rainfall or monsoon activity, it is critically necessary to manage excess accumulated water. To address this need, five types of facilities can be deployed: retention ponds, sedimentation tanks, tiered drainage systems, vegetative buffer strips, and flood regulation infrastructure. Balasuriya et al. (2022) confirm that these facilities can regulate stormwater discharge, thereby reducing flood peaks, protecting downstream water bodies, and stabilizing hydrological fluctuations. If plantations coordinate their drainage operations with regional hydrological management authorities, they can contribute to watershed-wide water resource management. Go et al. (2024) show that synchronized drainage across all plantations within the same catchment can lower watershed flood risk. However, this cross-stakeholder collaboration faces extremely high institutional barriers and can only be put into practice if four conditions, including the sharing of hydrological data, are met.

Hydrological governance frameworks play a decisive role in the water resource management performance of plantations. Currently, sustainability standards such as RSPO and ISPO have incorporated plantation water management into their compliance requirements, establishing four mandates: riparian zone protection, water body safeguarding, water quality monitoring, and maintenance of soil hydrological functions. Three types of tool environmental dashboards, digital reporting tools, and hydrology-focused audit systems—enhance management transparency and accountability and promote the alignment of multiple objectives. However, studies by Ho et al. (2024) and Sarkar et al. (2020) only confirm increases in the frequency of monitoring and reporting and lack long-term causal evidence linking compliance reforms to hydrological improvements.

Previous review studies have reached a core consensus: if water governance for plantation forests breaks through the boundaries of a single stakeholder and is embedded into a macro-level watershed management framework, governance effectiveness will improve significantly. Hamad et al. (2024) corroborates the conclusion: plantation forest operations that join watershed councils and multi-stakeholder hydrological committees can adopt integrated water governance practices, access comprehensive hydrological data, and participate deeply in risk management planning. Asad et al. (2024) further verify the multiple benefits of cross-stakeholder collaboration; However, existing literature rarely explores the impacts of four specific factors on participation in watershed governance: power asymmetry, land tenure, law enforcement capacity, and unequal access to technical information. This stands as the core knowledge gap in the current research field.

Technology adoption is a transformative dimension of contemporary water resources management. Four categories of digital hydrological technologies embedded in plantation management—satellite remote sensing, Internet of Things (IoT) hydrological sensors, drone monitoring, and hydroclimatic forecasting models—enable four core functions including the visualization of water resource allocation (Jaroenkietkajorn & Gheewala, 2021). Evidence that confirms the value of these technologies comes from real-world applications: digital elevation models can identify waterlogged low-lying areas to optimize drainage, and evapotranspiration models can improve irrigation precision (Abubakar et al., 2023). The core role of digital water management tools is to build a bridge between hydrological science and daily decision-making. However, if only large plantations can access the relevant technical resources while small-scale farmers are unable to gain access, this disparity will instead widen the gap in on-the-ground implementation. This study adopts systematic literature review methods to sort out the value, mechanisms, and limitations of ecological design in high-performance water management systems. This review demonstrates that ecological design is a core component of the target system. It identifies three categories of measures, including riparian buffer zones, that hold the dual value of supporting basic environmental functions and enabling hydrological regulation. This conclusion is corroborated by Manorama et al. (2024), who found that natural infrastructure such as vegetation only supports, rather than replaces, artificial water management systems. When paired with soil organic matter management and low-disturbance logging, these measures can improve sustainability. However, three categories of opportunity costs also exist, arising from the need to balance land allocation, maintenance investments, and conservation requirements with short-term production goals.

Climate variability is continuously increasing the need for adaptive water resource management in artificial plantations, as three categories of climate stress require plantations to maintain hydrological flexibility. Yusof et al. (2024) confirm that plantations adopting three types of climate tools: seasonal climate forecasts, drought risk maps, and rainfall anomaly indices which are better able to adjust their water management plans for extreme years. This paper identifies four on-the-ground water resources disaster prevention and control measures adapted to different climate scenarios: preserving soil moisture before droughts, temporarily shutting down drainage systems during low-rainfall periods, strengthening monitoring in El Niño years, and staggering harvests to avoid peak rainfall during wet seasons. These findings support a shift in hydrological management from a passive to a proactive approach, addressing the dual risks of floods and long-term drought.

The conclusion of this review is that integrating four dimensions of site-specific design, continuous monitoring, multi-scale governance, and adaptive planning can enhance the effectiveness of water resource management for plantation forests. The cross-interaction of these four dimensions can generate multiple hydrological benefits. Man et al. (2020) proposed that water resource systems should be structured to absorb and adapt to environmental variations rather than eliminate risks, thereby providing supporting evidence for this review. However, the studies included in the paper exhibit heterogeneity, so it is almost impossible to compare the effectiveness of intervention measures across different sites and different methods, and this flaw weakens the general ability of this review's conclusions.

This review synthesizes the available research evidence to answer the predefined research question. It clarifies that water resource management, which is integrated, adaptive, ecology-oriented, matches local hydrological conditions, and aligned with wider watershed governance frameworks is the optimal pathway to mitigate hydrological challenges and improve water governance performance. This pathway is increasingly common in modern plantations, driven by technological progress, regulatory requirements, and the evolution of sustainability frameworks. This review does not support the claim that this pathway is universally effective; its positive outcomes require the fulfillment of six conditions.

The insights of this review are divided into two primary levels. The first level proposes that improving water management cannot rely only on infrastructure construction but must also be supported by four non-infrastructure conditions: governance capacity, data accessibility, cross-scale coordination, and climate-adaptive decision-making; efficiency can be boosted through three types of measures: deploying monitoring technologies, refining hydrological modeling, and rolling out training programs. The second level emphasizes that water systems do not operate independently, requiring that plantation strategies be embedded into watershed hydrological planning to align the water demands of three types of stakeholders, and mandating that future models integrate four core elements.

For water resource management in oil palm landscapes, this study proposes four future research tasks: First, it is necessary to rely on long-term hydrological datasets to clarify the cumulative effects of water resource management in peat-dominated climate-sensitive regions. Second, coordinated comparative research on drainage coordination across multiple plantations within shared river basins must be carried out to generate insights for catchment optimization. Third, technologies including digital hydrology must be studied to strengthen the relevant scientific foundation; and finally, the hydrological effectiveness and practical implementation feasibility of relevant management plans must be evaluated from multiple dimensions.

Conclusion

This review synthesized 35 eligible studies on water resource management in oil palm plantations across diverse biophysical and climatic contexts. As a review study in the field of water resources governance for oil palm landscapes, this paper challenges the long-dominant traditional water governance approach that relies solely on isolated technical interventions. It supports a multi-dimensional adaptive governance pathway that integrates five core elements, including hydrological processes and infrastructure design. This study also finds that water management performance is shaped by the complex interactions of six site-specific elements, such as soil type and rainfall patterns, drainage conditions, plantation age, management capacity, and institutional context. This review, through the synthesis of the included evidence, finds that the water-related challenges facing plantation-covered peatlands, mineral soils, sloped lands, humid regions, and dry-season production zones differ significantly. These differences are the core reason why the effectiveness of management strategies varies across locations. Water management for plantations has five closely linked core components: erosion prevention and control, drainage regulation, groundwater management, soil moisture retention, and water quality protection. The soil and water conservation measures proposed in this study fall into two categories. Physical measures, including practices such as contour farming, reduce sediment production and control water flow. Digital measures, including tools such as automatic water level recorders, improve the accuracy of decision-making. Only, when implemented independently; must they be paired with routine monitoring, dedicated planning, and cross-scale coordination, and only when rolled out as an integrated package can they deliver maximum effectiveness.

The practical implication of this study is that, for relevant stakeholders including plantation managers, policymakers, certification bodies, and smallholder farmer support organizations, one-size-fits-all water resource management guidelines for planted forests must be abandoned. Implementing a combination of measures such as drainage management, soil protection, riparian zone protection, and groundwater level monitoring can improve the resilience of planted forests, meet environmental compliance requirements, protect downstream water resources, and secure long-term stable production. This review has several limitations that must be explicitly acknowledged: only accessible English-language studies indexed in Scopus were included, which may have omitted relevant evidence from other databases, non-English literature and other related sources; the included studies showed high heterogeneity, making it impossible to produce a standardized quantitative estimate of the intervention's effectiveness. This paper provides a thematic synthesis of existing relevant evidence in the field of hydrological management of oil palm plantations. Future research needs to advance along two major directions. Methodologically, multi-site comparative studies should be conducted to clarify the cumulative effects of peatlands and mineral soils systems. From an implementation perspective, future studies should evaluate the practical feasibility of factors including maintenance costs and smallholder capacities, to balance the hydrological benefits and operational practicality of this landscape.

Study Limitations

Several limitations of the systematic review should be acknowledged. The review was limited to Scopus-indexed open-access literature, which means that relevant studies indexed in other databases, published in other languages, or available only behind paywalls may have been excluded. While this methodology helped ensure that the full-text materials were available for verification, it also introduces potential selection bias because the final corpus reflects accessible Scopus literature rather than the entire global evidence base on oil palm water management. Second, there was high heterogeneity regarding the methods used in the studies that have been reviewed; differences include study design and spatial scale (e.g., plot-scale or plantation block or catchment), as well as differences in monitoring duration, hydrological indicators, sampling frequency, and measurement protocols. This degree of heterogeneity restricted comparability of the reported outcomes and precluded formal meta-analysis. Therefore, the numerical values reported in this review should be interpreted as study-specific evidence rather than standardized estimates of intervention effectiveness. Third, the preponderance of research was based on short- to medium-term monitoring efforts which limited the ability to assess the long-term effectiveness and longevity of conservation interventions across spatially heterogenous climatic and management gradients. Finally, operational and economic dimensions of conservation practices (e.g. installation cost, materiel, labor requirement, and maintenance demands) were reported inconsistently across the included studies. This limits the comparability of results relating to cost-effectiveness and practical viability across different plantation contexts. These limitations are particularly important for smallholder systems, where financial capacity, technical support, and institutional access may differ substantially from large estate plantations.

Recommendations for Future Research

The synthesis identified critical knowledge gaps that warrant further investigation. First, long-term data are required to evaluate the persistent effects of conservation practices throughout complete plantation cycles, particularly during abnormally high precipitation events. Second, future efforts should employ standardized measurement protocols that include harmonized indicators for runoff, infiltration, water-table fluctuation, sediment transport, nutrient leaching, soil organic carbon, and water quality. More standardization would facilitate comparability between sites and allow for stronger quantitative synthesis. Third, more studies should include economic and operational analyses such as transparent reporting of installation costs, maintenance requirements, labor needs beyond cost–benefit trade-offs. All these aspects are important to evaluate feasibility in both estate and smallholder systems. Fourth, even though plantations are location specific, future work landscape-scale and catchment-scale conservation approaches that integrate 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 distinguish context-specific findings from more generalizable mechanisms that regulate soil and water conservation in oil palm systems. Such research would strengthen the evidence base by linking hydrological effectiveness with engineering feasibility, socioeconomic constraints, and governance capacity.

Practical and Theoretical Implications

Practical Implications

These findings provide evidence-based guidance for plantation managers, policymakers and sustainability certification systems. Accordingly, the review suggests that conservation practices should be implemented through tiered and site-specific approaches rather than through one-size-fits-all prescriptions. Structural, vegetative and landscape measures are most effective when chosen according to topography, rainfall regime, soil type, drainage sensitivity, and hydrological risk. Doing so can help optimize conservation design through integrated intervention packages, such as combining groundcover management, contour structures, sediment traps, riparian buffers, and controlled drainage systems according to slope class, erosion risk, and water-table conditions. Routine maintenance should also be treated as part of water-management design, including periodic canal desilting, sediment-trap cleaning, vegetation management, and inspection of water-control structures. This information is particularly timely for supporting the biophysical data requirements of Best Management Practice (BMP), sustainability certification and plantation planning frameworks as they seek to balance environmental protection with operational viability. For practical implementation, however, managers and policymakers should consider not only technical effectiveness but also installation costs, labor availability, monitoring capacity, and the ability of smallholders to adopt and maintain recommended practices.

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 technical interventions. The synthesis stresses that conservation practices should be evaluated at interacting spatial scales, from plot-scale interventions to landscape-scale hydrological control. This review advances the conceptualization of plantation water governance by merging evidence from structural and vegetative as well as spatial planning measures. Moreover, this study underscores the need for implementation-oriented environmental research, in which technical effectiveness and institutional, economic and operational barriers to adoption are evaluated in practice. The main theoretical implication is that water management in oil palm plantations should be understood as a socio-technical and eco-hydrological system, in which engineering design, soil-water processes, climate variability, institutional rules, and management capacity jointly shape outcomes.

Statements and Data Availability Statement

Data Availability Statement

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

Conflict of Interest

There are no conflicts of interest related to the publication of this manuscript. The research was done in the absence of any commercial or financial relationships that could be considered a potential conflict 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 Declaration

AI-assisted language tool was utilized during the preparation of this manuscript, however, only to assist with some 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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