



From El Niño Drought Recovery to Climate Resilience: An Integrated Water-Soil-Plant Management Framework for Oil Palm Plantations in East Kalimantan, Indonesia

Loso Judijanto
IPOSS Jakarta

Corresponding Author: Loso Judijanto losojudijantobumn@gmail.com

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ABSTRACT

Prolonged El Niño drought creates a compound challenge for oil palm plantations because water deficits affect not only current photosynthesis and nutrient uptake but also reproductive development and subsequent fresh fruit bunch production. This qualitative literature review synthesizes contemporary evidence published mainly during 2020–2026 to develop an integrated recovery and climate-resilience framework applicable to oil palm plantations in East Kalimantan, Indonesia. Particular attention is given to recovery fertilization, empty fruit bunch and compost application, land application of organic residues, pest and disease surveillance, stopbund regulation, understory and Nephrolepis management, frond management, superabsorbent polymers for legume establishment, integrated water management, conservation terraces, and drought-resilient planting materials. The synthesis shows that water restoration should precede intensive nutritional recovery because fertilization cannot fully compensate for yield losses when water remains the principal limiting factor. Organic residues, controlled understory vegetation, and frond recycling can strengthen soil structure, nutrient cycling, soil organic carbon, and hydrological buffering. Stopbunds should be operated dynamically according to rainfall, soil moisture, drainage status, and topography rather than calendar dates

INTRODUCTION

Oil palm (*Elaeis guineensis* Jacq.) is a perennial tropical crop whose productivity depends on the interaction between genetic potential, soil conditions, nutrient availability, canopy development, plantation management, and atmospheric water supply. Its perennial character creates a particular form of climate vulnerability because stress experienced during one season may influence reproductive development and yield long after rainfall has returned. In contrast with annual crops, where drought impacts are often concentrated within a single growing cycle, oil palm maintains overlapping vegetative and reproductive processes extending over several years. Water deficits may therefore alter photosynthesis and biomass accumulation immediately while simultaneously affecting inflorescence differentiation, sex determination, abortion, bunch development, and fresh fruit bunch (FFB) production many months later (Monzon et al., 2022; Hermanto et al., 2023; Kamil et al., 2024).

This problem is particularly important under strong El Niño events. ENSO-related rainfall anomalies can reduce soil moisture and increase atmospheric vapour pressure deficit, resulting in simultaneous edaphic and atmospheric drought. Long-term plantation observations have shown that water stress and vapour pressure deficit are major determinants of spatial and temporal variation in oil palm productivity, while extreme climate anomalies may have nonlinear effects on yield over different pre-harvest periods (Monzon et al., 2022; Kamil et al., 2024). Climate-change studies further indicate that increasingly variable rainfall, higher temperatures, drought episodes, and interactions with pest and disease pressures are becoming central constraints for the future sustainability of oil palm cultivation in Southeast Asia (Sarkar et al., 2020; Abubakar et al., 2021; Murphy et al., 2021). Malaysian time-series evidence similarly links El Niño intensity with prolonged FFB losses, indicating that production effects can persist well beyond the meteorological event itself. (Khor et al., 2021)

The operational context of East Kalimantan in September 2026 provides a particularly relevant example. Although plantation managers may already be planning a “post-El Niño” recovery programme, meteorological drought can remain active even when isolated rainfall events begin to occur. Consequently, one of the most important distinctions for plantation decision-making is between the first return of rain and genuine hydrological recovery. A single rainfall event may wet the surface while deeper root-zone water deficits remain substantial. Likewise, the opening of water-control structures immediately after early rainfall may discharge water that could otherwise contribute to soil-profile recharge. Recovery interventions therefore need to be triggered by hydrological indicators rather than merely by the calendar. For September 2026 specifically, monitoring by the Badan Meteorologi, Klimatologi, dan Geofisika (BMKG) indicates that very strong El Niño conditions and meteorological drought risk remain relevant to parts of East Kalimantan, making calendar-based assumptions of complete post-El Niño recovery premature. (BMKG, 2026a, 2026b)

Drought also complicates fertilizer management. Nutrient uptake depends on root activity, soil water, nutrient diffusion and mass flow, and physiological demand. Increasing fertilizer rates during severe moisture limitation does not automatically increase nutrient acquisition. Evidence from long-term Indonesian fertilizer trials shows that improved nutrition substantially enhances yield under favourable conditions but has limited capacity to compensate for climate-driven yield reductions when water stress is severe (Wandri et al., 2025). Recovery fertilization should therefore be understood as a carefully timed restoration strategy rather than simply an “extra fertilizer” programme. Nutrient diagnosis, soil moisture status, split application, balanced N-P-K-Mg-B nutrition, and expected rainfall all become important components of the decision. Evidence from irrigated mature palms also shows that fertilizer response is conditioned by water availability, while critical leaf-nutrient ranges can improve the precision of nutrient prescriptions. (Arifin et al., 2022; Kamireddy et al., 2023)

Organic inputs provide a second important intervention pathway. Empty fruit bunches (EFB, locally JJK), composted residues, palm oil mill by-products where permitted for land application, and pruned fronds can return nutrients and organic carbon to plantation soils. Long-term evidence from Sumatra indicates that EFB application can improve soil carbon pools and that management zones receiving frond residues can exhibit greater microbial biomass, organic carbon, nutrient cycling, and lower bulk density than intensively cleared plantation zones (Rahman et al., 2021; Formaglio et al., 2021; Noirot et al., 2022). These processes are particularly relevant to drought resilience because organic matter affects aggregate stability, infiltration, biological activity, and soil-water buffering. Recent synthesis and field evidence further support EFB as a soil amendment capable of improving soil chemical and structural attributes, although the magnitude of hydrological benefits remains soil- and treatment-specific. (Adu et al., 2022; Nyasapoh et al., 2026)

Management of ground vegetation requires similar reconsideration. The conventional objective of plantation sanitation may encourage aggressive removal of understory vegetation. However, contemporary research indicates that understory vegetation can provide soil structural, microclimatic, biodiversity, nutrient-retention, and erosion-control functions, although unmanaged vegetation can also compete for water and nutrients under severe drought (Hood et al., 2020; Yahya et al., 2022; Thoumazeau et al., 2024). The management question is therefore not whether all ground vegetation should be eliminated, but how useful vegetation can be selectively retained, slashed, or recycled without compromising harvesting operations, sanitation, or water availability to palms. Management intensity also matters because large-scale plantation evidence indicates that herbicide-based weed control can increase nutrient leaching relative to mechanical weeding, reinforcing the case for selective rather than indiscriminate vegetation suppression. (Formaglio et al., 2020)

The same principle of conditional management applies to stopbunds and drainage infrastructure. Oil palm landscapes need to perform two apparently opposing hydrological functions: retain and harvest water when water is scarce, yet discharge excessive water safely during prolonged rainfall or flooding. Climate resilience therefore requires a transition from drainage-oriented management toward an integrated retain-store-redistribute-drain system. This principle is especially important where plantation hydrology interacts with peat, marginal soils, slopes, river systems, or seasonal flooding (Akram et al., 2022; Warren-Thomas et al., 2022; McCalmont et al., 2023; Asmara and Randhir, 2024). Long-term adaptation must extend beyond annual management. Replanting provides a rare opportunity to redesign field infrastructure through contour alignment, conservation terraces, water-retention features, road and drain redesign, and improved ground-cover establishment. Genetic adaptation is similarly important. Recent physiological, transcriptomic, molecular-marker, and multiseasonal-yield studies show meaningful variation among oil palm materials in their responses to drought, but drought tolerance is multidimensional and should be validated against mature-palm productivity and local environmental conditions rather than assumed from a single nursery trait (Wang et al., 2020; Salgado et al., 2022; Hermanto et al., 2023; Suraninpong et al., 2023; Bayona-Rodríguez and Romero, 2024; Montoya et al., 2024).

Against this background, this article addresses seven interrelated questions. It first asks how prolonged El Niño drought affects oil palm physiological and reproductive processes and which quick-win interventions are supported by contemporary evidence. It then examines how fertilization and organic inputs should be sequenced, how stopbunds and water infrastructure can support both drought and flood management, and how understory vegetation and frond management can support recovery without intensifying competition. Finally, it considers whether superabsorbent polymers are justified for cover-crop establishment and how water engineering, conservation-oriented replanting, and drought-resilient genetics can improve long-term plantation resilience.

The objective is therefore to develop an integrated water-soil-plant management framework that distinguishes emergency drought stabilization, hydrological recovery, physiological recovery, and structural climate adaptation. The article does not propose a universal fertilizer dose, water-table level, or stopbund schedule. Instead, it develops evidence-based decision principles that can subsequently be converted into site-specific standard operating procedures using estate rainfall, soil, topography, water-table, leaf-analysis, pest, and productivity data.

LITERATURE RIVIEW

1. Drought as a Soil-Plant-Atmosphere Problem

Oil palm drought stress cannot be explained by rainfall alone. Plant water status reflects the interaction between precipitation, soil water-storage capacity, rooting conditions, evapotranspiration, temperature, humidity, wind, canopy condition, and atmospheric vapour pressure deficit. Consequently, two plantation blocks receiving similar rainfall may experience different physiological stress if their soils, rooting depths, organic matter, slope positions, or atmospheric demand differ. Simulation studies further suggest that oil palm water requirements can be substantial and may be underestimated when represented by a single generalized evapotranspiration value across palm ages and environments (Akram et al., 2022).

At the leaf level, declining soil-water availability induces stomatal closure as the palm attempts to reduce transpiration. Prolonged stress subsequently limits carbon assimilation through both stomatal and non-stomatal mechanisms. Experiments with young oil palms exposed to repeated water-deficit cycles have demonstrated rapid dehydration, reductions in net photosynthesis, and physiological acclimation after recurrent stress events (Lopes Filho et al., 2021). Metabolomic studies further indicate substantial biochemical reconfiguration during drought, while transcriptomic analyses reveal altered expression of genes involved in cell-wall processes, transport, phenylpropanoid metabolism, homeostasis, and stress signalling (Wang et al., 2020; Rodrigues Neto et al., 2021). Oil palm responses are therefore not simply passive consequences of water shortage. The plant activates osmotic regulation, antioxidant defence, hormonal responses, metabolic adjustment, and changes in gene expression. MicroRNA studies demonstrate extensive drought-responsive regulatory changes, illustrating that water deprivation affects post-transcriptional regulation as well as visible plant growth (Salgado et al., 2022). Such physiological complexity helps explain why palms may require time to recover even after rainfall resumes.

Atmospheric drought also deserves attention. Monzon et al. (2022) demonstrated the importance of vapour pressure deficit in explaining FFB variation in Indonesia and found negative relationships between VPD, yield, and water-use efficiency. Thus, soil that is becoming wetter does not necessarily imply complete physiological recovery if atmospheric demand remains extremely high. Estate monitoring systems should consequently integrate rainfall and soil moisture with temperature and relative humidity, enabling VPD to be estimated as an additional drought indicator. Eddy-covariance analysis from an Indonesian oil palm plantation during the 2015 El Niño likewise shows marked shifts in carbon-water coupling and water-use efficiency across wet, dry, and haze-affected periods. (Rinandyta and June, 2025)

2. Delayed Reproductive and Yield Effects

A central problem in managing post-drought oil palm is the time lag between climatic stress and visible production consequences. Oil palm reproductive development occurs over an extended period. Climatic anomalies occurring during sex differentiation, inflorescence development, anthesis, abortion-sensitive stages, or bunch development may alter bunch number and

subsequent yield. Monzon et al. (2022) identified weather conditions during bunch failure, anthesis, and sex differentiation as major contributors to yield variation.

Hermanto et al. (2023) likewise used multiseasonal yield and rainfall records to identify sensitive reproductive stages and found bunch number to be particularly informative when assessing drought responses. Their work showed that rainfall variation affected inflorescence abortion and sex determination and also demonstrated genotype-specific yield responses. Thus, lower FFB production after rainfall has normalized should not automatically be interpreted as failure of a recovery programme; part of the production decline may have been biologically programmed months earlier.

This lag has important implications for management evaluation. If extra fertilizer is applied immediately after rainfall returns, managers may expect a rapid yield response and conclude that fertilization has failed if FFB production remains depressed. A more appropriate evaluation system separates leading indicators—soil moisture, leaf nutrient status, canopy condition, new frond development, reproductive observations—from lagging indicators such as harvested FFB. Short-term recovery should therefore be judged partly through physiological and agronomic indicators before full yield recovery becomes observable.

3. Nutrient Recovery after Drought

Nutrient deficiencies already constrain oil palm productivity in many Indonesian production systems. Sugianto et al. (2023) reported widespread potassium, nitrogen, boron, phosphorus, and magnesium deficiencies in surveyed smallholder fields, while Lim et al. (2023) found that nutrient applications were frequently insufficient, unbalanced, incorrectly placed, or inadequately split. Potassium is particularly important for oil palm, and field experiments in Sumatra demonstrate substantial site-specific yield responses to K and Mg fertilizer, with nutrient recovery efficiency influenced by rainfall, soil properties, slope, and moisture deficit (Prabowo et al., 2023). Establishing critical leaf nutrient concentrations provides an additional basis for diagnosis-led fertilization and for distinguishing true nutrient limitation from drought-induced constraints on uptake. (Kamireddy et al., 2023)

These findings strengthen the case for correcting genuine deficiencies after drought but do not justify undifferentiated fertilizer escalation. Wandri et al. (2025) evaluated long-term fertilizer trials in Indonesian water-limited environments and demonstrated that high nutritional status increased yield markedly during favourable periods, but improved nutrition provided little protection against the most severe water-driven low-yield periods. Water availability therefore functions as a gating factor for nutrient response.

Recovery fertilization should accordingly follow four principles. First, confirm whether water has sufficiently returned to the effective root zone. Second, diagnose actual nutritional constraints through leaf analysis, soil information, previous fertilizer history, and expected yield. Third, use balanced rather than single-nutrient correction because drought and prior production may alter multiple nutrient pools. Fourth, divide applications where feasible to reduce

nutrient-loss risks and better synchronize nutrient supply with renewed root uptake.

Nutrient recovery must also consider fertilizer placement and competition. De Vos et al. (2021) and Mettauwer et al. (2021) showed that management practices, fertilizer use, planting material, harvesting, and economic optimization strongly influence plantation performance. More intensive fertilizer use does not automatically generate the optimum economic outcome. Therefore, “extra fertilizer” during drought recovery should be defined agronomically and economically: additional input should be applied when diagnosis demonstrates a likely response, not simply because drought occurred.

4. EFB, Compost, Land Application and Soil Organic Matter

Organic residue recycling provides an important bridge between fertility management and drought resilience. Oil palm plantation soils can experience declining soil organic carbon depending on previous land use and management intensity. Rahman et al. (2021) demonstrated differences in SOC stocks under contrasting plantation management, emphasizing the role of management in retaining carbon within established oil palm systems.

Long-term EFB studies strengthen the evidence for systematic residue recycling. Noirot et al. (2022) found that EFB treatments affected SOC and labile carbon pools, with relatively frequent applications contributing to improved carbon sequestration in plantation soil. The study also showed that responses depended on application strategy, indicating that extremely high episodic doses are not necessarily superior to better-designed recurring applications.

Rudolf et al. (2021) linked mulching practices with soil characteristics and plantation outcomes, highlighting opportunities to improve both environmental and economic performance. Organic mulch protects the surface from direct solar radiation and raindrop impact, adds carbon and nutrients, moderates temperature, and creates a more favourable habitat for soil organisms. During drought recovery, these functions become particularly valuable because soil that is structurally degraded or bare may lose newly returned rainfall rapidly through runoff or evaporation. A meta-analysis of EFB use and newer tropical-soil experiments further indicate improvements in soil fertility, organic carbon, bulk density, and selected water- and gas-transport properties, although responses to available water are not uniformly positive across soils. (Adu et al., 2022; Nyasapoh et al., 2026)

Pruned fronds offer another substantial internal resource. Formaglio et al. (2021) showed that frond-stacked zones in Sumatra displayed greater microbial biomass, soil organic carbon, extractable carbon and nitrogen, and improved internal nitrogen cycling compared with intensively managed palm circles and inter-rows. Frond placement is therefore not merely an operational issue but part of plantation nutrient cycling and soil rehabilitation.

Land application of appropriately treated palm oil mill residues can also contribute nutrients and organic matter where permitted and agronomically suitable. However, application rates should account for nutrient loading, drainage, soil type, water quality, and environmental regulations. Organic residues should complement rather than automatically replace mineral fertilizers

because nutrient release patterns differ substantially between organic materials and soluble fertilizers.

5. Understory Vegetation, GCC and Nephrolepis

Management of ground cover following drought requires balancing water competition against soil protection. Complete removal of vegetation may temporarily reduce competing transpiration, but it also increases soil exposure, erosion, surface temperature, and potential runoff after intense rainfall. Studies of vegetation-management regimes in mature oil palm show that maintaining understory complexity can support ecosystem functions without necessarily reducing plantation performance (Hood et al., 2020; Pashkevich et al., 2022).

Yahya et al. (2022) reviewed the role of understorey vegetation in sustainable oil palm cultivation and emphasized that vegetation should be evaluated according to its competitive effects and its contributions to soil protection, nutrient balance, water processes, biodiversity, and plantation function. Species such as *Nephrolepis biserrata* may provide useful soil cover in appropriate conditions. Similarly, Satriawan et al. (2023) examined *Asystasia* as ground cover in relation to plantation water balance, illustrating the need to evaluate vegetation function rather than treating all non-palm vegetation simply as weeds.

Thoumazeau et al. (2024) found that understory vegetation was positively associated with indicators of soil structure maintenance in Indonesian oil palm smallholdings, while potassium fertilization was important for palm performance. The result supports an integrated approach in which vegetation and fertilizer management are not treated as opposing alternatives. Soil health and crop nutrition can be managed together.

For drought recovery, selective slashing is therefore more defensible than indiscriminate clearing. Vegetation immediately competing around palm circles or interfering with field operations may need to be controlled, while useful cover between rows can be maintained at a manageable height. Slashed biomass should generally remain in situ where disease and operational considerations permit, converting competitive live vegetation into protective surface mulch and eventually organic matter. This preference for targeted mechanical control is also consistent with evidence that mechanical weeding can reduce nutrient-leaching losses compared with herbicide-based weed control in oil palm plantations. (Formaglio et al., 2020)

Microclimatic evidence provides additional support for structural vegetation management. Somenguem Donfack et al. (2021) showed that biodiversity enrichment within oil palm systems can affect microclimate and land-surface temperatures. Although enriched agroforestry configurations are not directly equivalent to commercial understory, the broader implication is relevant: vegetation structure influences the plantation energy and moisture environment.

6. Frond Management and Canopy Recovery

Frond management following severe drought requires caution because excessive pruning removes photosynthetically active area at the same time the palm needs carbon to rebuild physiological function. Necessary harvesting

access and sanitation must still be maintained, but drought-stressed palms should not be subjected to unnecessary canopy reduction.

The importance of fronds extends beyond photosynthesis. After pruning, fronds become one of the plantation's largest recurring organic inputs. Frond stacking contributes to nutrient cycling and soil biological activity, while decomposing biomass protects soil from heat and physical disturbance (Formaglio et al., 2021). Under drought-recovery conditions, disciplined frond arrangement can therefore simultaneously preserve field accessibility, support organic-matter restoration, and improve soil microenvironments.

Frond management should consequently be incorporated into a broader canopy–soil recovery strategy. Estate monitoring should identify palms with severe desiccation, excessive dead fronds, crown abnormalities, or delayed spear development, while standard pruning policy should protect sufficient functional frond area. The objective is not maximal leaf retention irrespective of harvesting requirements, but avoidance of unnecessary additional stress.

7. Pest and Disease Risk during Recovery

Climatic stress may alter host susceptibility, pest population dynamics, pathogen development, biological control, and field accessibility. Murphy et al. (2021) identify climatic resilience and pest and disease management as major strategic challenges for global oil palm production. Ganoderma basal stem rot remains particularly important in Southeast Asian plantations, with climate, management, planting cycles, and site conditions potentially interacting with disease outcomes (Paterson, 2020; Flood et al., 2022; Paterson, 2023).

The implication for the proposed recovery programme is not to increase pesticide applications prophylactically but to intensify surveillance. Drought-stressed or recovering blocks should be mapped according to prior pest history, canopy symptoms, Ganoderma incidence, defoliator occurrence, rodent damage, and beneficial-organism status. Integrated pest management is especially important because elimination of beneficial understory or indiscriminate chemical use may reduce natural control functions.

Research on biological and integrated approaches further demonstrates that disease management requires preventive and system-level strategies rather than isolated curative treatment (Rebitanim et al., 2020). Contemporary reviews of oil palm insect management also emphasize monitoring, ecological understanding, and integrated control rather than reliance on a single intervention.

8. Integrated Water Management and Stopbund Operation

Water management is the central organizing principle of drought recovery. During severe drought, the objective is to minimize avoidable water losses and maximize capture of available rainfall. As rainfall becomes more regular, the objective changes from emergency retention toward redistribution and root-zone replenishment. Once the wet season becomes established, excessive water must be discharged safely while maintaining reserves for the next dry phase.

This requires stopbunds to be treated as adjustable hydrological infrastructure rather than static structures. Opening all stopbunds immediately

after the first substantial rain risks losing valuable water before deeper soil profiles have recovered. Conversely, retaining all water during increasingly wet conditions may create prolonged waterlogging, road damage, root-zone hypoxia, nutrient losses, or flooding.

The correct trigger therefore depends on measurable conditions: recent cumulative rainfall; rainfall frequency; soil moisture at representative depths; water levels in field drains and collection drains; water-table depth in peat; reservoir and retention-pond storage; field accessibility; topography; and short-term rainfall forecasts. Different blocks may require different operating decisions within the same estate.

Landscape-scale studies support this integrated interpretation. Asmara and Randhir (2024) modelled oil palm impacts on water quantity and quality in an Indonesian watershed and demonstrated that plantation hydrology influences runoff, sediment, and nutrient transport. Water management therefore cannot be reduced to drainage at the individual palm level. Field drains, roads, culverts, bunds, streams, storage ponds, and downstream water bodies must be treated as a connected network.

Safitri et al. (2026) further assessed the climate-smartness of alternative agronomic practices under changing climate scenarios and found strong adaptation potential associated with irrigation, while also demonstrating trade-offs among productivity, carbon, water, and emissions outcomes. Their findings reinforce the need to treat water management as a strategic climate-adaptation investment rather than merely an emergency drought response.

METHODOLOGY

1. Qualitative Literature Review Design

This study adopts a qualitative literature review rather than a systematic literature review. The purpose is interpretive and integrative: to bring together heterogeneous evidence on oil palm drought physiology, reproductive responses, nutrient management, organic residues, vegetation management, water control, pests and diseases, soil conservation, superabsorbent polymers, and genetic resilience. Because these topics involve different experimental designs, scales, countries, soil types, and outcome variables, a qualitative thematic synthesis is more appropriate than formal meta-analysis.

The review nevertheless uses transparent principles of source selection. Priority was given to peer-reviewed journal publications from 2020–2026 indexed by major academic databases and published by established journals and publishers. Indonesian and Southeast Asian studies were prioritized for plantation-management questions, while evidence from other oil-palm-growing regions was incorporated where it clarified physiological or genetic mechanisms. Evidence from other crops was included selectively for superabsorbent polymer technology because direct mature-oil-palm evidence remains limited.

The literature search employed combinations of terms including “oil palm”, “El Niño”, “drought”, “water deficit”, “vapour pressure deficit”, “water management”, “fertilizer”, “potassium”, “magnesium”, “empty fruit bunch”, “organic mulch”, “soil organic carbon”, “understory”, “*Nephrolepis*”, “cover crop”, “frond management”, “peat water table”, “*Ganoderma*”, “superabsorbent

polymer", "hydrogel", "drought tolerance", "genotype", "molecular marker", and "climate-smart oil palm". Searches were iterative rather than protocol-locked because the objective was conceptual saturation and thematic integration, not estimation of a pooled treatment effect.

Sources were interpreted according to geographical relevance, experimental scale, palm age, soil condition, climatic setting, and study design. Particular caution was applied when transferring findings from nursery seedlings to mature commercial palms or from non-oil-palm crops to plantation cover-crop establishment.

Current climate information for East Kalimantan was treated as contextual evidence rather than part of the peer-reviewed literature corpus. Official Indonesian meteorological information was used to distinguish ongoing drought conditions from actual post-El Niño recovery. This distinction is essential because the agronomic recommendations developed here depend on actual hydrological state rather than a predetermined seasonal date

RESULT

1. Theme 1: Drought Recovery Has a Long Biological Tail

The literature consistently indicates that oil palm drought damage extends beyond the period when rainfall is visibly deficient. Immediate responses include lower stomatal conductance, transpiration, and photosynthesis, while longer-term effects involve reproductive development and subsequent bunch production (Lopes Filho et al., 2021; Rodrigues Neto et al., 2021; Monzon et al., 2022).

This delayed response creates what may be termed a drought legacy. Even if soil-water status improves rapidly, reproductive structures that experienced stress months earlier may still produce lower bunch numbers or higher abortion. Hermanto et al. (2023) demonstrated the usefulness of multiseasonal yield data for separating genotype-specific responses and identifying sensitive floral stages. Production recovery should therefore be evaluated over an extended time horizon rather than several weeks after rainfall resumes.

The finding also has practical implications for estate budgeting. FFB delivery to mills may remain below normal after the wet season returns, requiring adjustment of labour, harvesting, transport, and processing plans. Managers should avoid interpreting lagged production losses as evidence that current recovery interventions are ineffective.

2. Theme 2: Water Is the Gating Resource

Across the evidence reviewed, adequate water emerges as the primary precondition for effective recovery. Fertilizer can alleviate nutritional constraints, organic residues can improve soil function, and genetic adaptation can improve drought tolerance, but no intervention eliminates the fundamental requirement for water.

The most direct evidence comes from Indonesian production studies. Monzon et al. (2022) identified water stress and VPD as key determinants of yield variation. Wandri et al. (2025) subsequently showed that improved nutrition increased production potential but had limited capacity to protect yield during

severe water-limited cycles. Prabowo et al. (2023) similarly found fertilizer recovery efficiency to be negatively associated with soil moisture deficit.

This leads to a fundamental operational rule: **do not interpret the first rainfall event as full recovery of plant-available water**. Hydrological recovery should be verified through cumulative rainfall and root-zone soil moisture, with additional water-table observations where relevant.

As illustrated in Figure 1, climate stress should not be connected directly to current-month FFB alone. The relevant causal pathway passes through soil water, atmospheric demand, plant physiology, and reproductive development. This explains why management during the current drought can influence production far beyond the date when rainfall eventually normalizes.

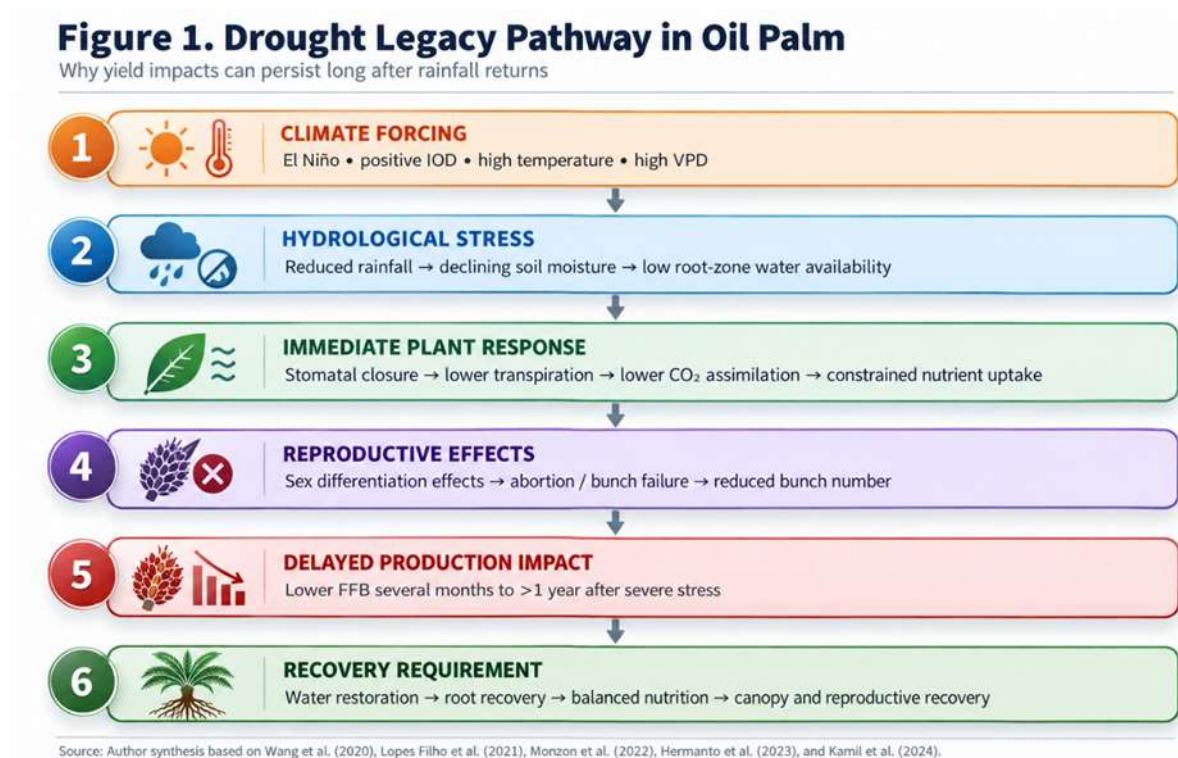


Figure 1. Drought Legacy Pathway in Oil Palm

Source: Author Synthesis Based on Akram Et Al. (2022), Warren-Thomas Et Al. (2022), Mccalmon Et Al. (2023), Asmara and Randhir (2024), and Safitri Et Al. (2026).

The figure further clarifies why recovery should be sequenced. Water recovery precedes strong nutrient response, while production recovery may occur later because reproductive stages affected previously cannot be completely reversed by subsequent fertilization.

3. Theme 3: Recovery Fertilization Should Be Conditional, Balanced and Split

The literature supports improved nutrient management but not indiscriminate fertilizer escalation. Sugianto et al. (2023) and Lim et al. (2023) demonstrate that nutrient deficiencies and imbalances remain common and can substantially constrain yield. Prabowo et al. (2023) show that K and Mg fertilizer responses vary with rainfall, soil, slope, and moisture conditions. Ruiz-Romero

et al. (2024) additionally demonstrate that drought responses can interact with nitrogen form and genotype even at seedling level.

The quick-win recommendation of “extra fertilization” should therefore be reformulated as diagnosis-based recovery fertilization. The first decision is whether the effective root zone is wet enough to support nutrient uptake. The second is whether leaf, soil, production, or fertilizer-history data indicate deficiency. The third is selection of nutrient source, rate, placement, and number of splits. The fourth is operational synchronization with subsequent rainfall.

High-dose application immediately before unreliable rainfall increases the risk of poor nutrient recovery. On steep or erosion-prone fields, intense rainfall following fertilizer application may also increase nutrient transport away from intended rooting zones. A split programme reduces exposure to these risks and provides opportunities to adjust later applications according to rainfall and palm response.

4. Theme 4: Organic Residues Function as Biological Water Infrastructure

EFB/JJK, compost, pruned fronds, and appropriate organic land application should not be viewed only as nutrient substitutions. Their more strategic value is that they contribute to a soil environment capable of receiving, storing, and biologically processing rainfall.

Rahman et al. (2021), Rudolf et al. (2021), Formaglio et al. (2021), and Noirot et al. (2022) collectively show that residue management influences soil carbon, nutrient cycling, microbial activity, bulk density, and soil function. Finstad et al. (2020) also highlight the importance of land-use and management history for soil-carbon dynamics in oil palm landscapes.

In drought-prone plantations, soil organic matter can thus be conceptualized as part of water infrastructure. Conventional infrastructure stores water above ground in ponds, drains, reservoirs, and bunded areas. Organic-matter management improves the capacity of the rooting environment to infiltrate and retain a larger fraction of available water. The two strategies are complementary.

5. Theme 5: Understory Management Should Shift from Elimination to Functional Regulation

Evidence does not support a universal recommendation to remove all understory vegetation. Understory plants can compete with palms for resources, particularly during extreme drought, but they also reduce exposed soil, contribute biomass, improve soil structure, and support ecological functions (Hood et al., 2020; Yahya et al., 2022; Pashkevich et al., 2022; Thoumazeau et al., 2024).

The proposed slashing of GCC or *Nephrolepis* should consequently be selective. In severely dry areas, vegetation immediately around palms may need stronger control to reduce competition. Elsewhere, controlled slashing can reduce above-ground water demand while retaining roots and dead biomass that protect the soil. Slash material can remain as mulch where it does not increase unacceptable pest, disease, or operational risk.

This approach also reduces the danger of creating bare soil immediately before the wet season. Bare inter-rows receiving intense convective rainfall may experience greater splash erosion, runoff, crusting, and nutrient displacement. Jaya et al. (2023) illustrate the broader erosion consequences associated with conversion and plantation conditions, strengthening the rationale for continuous soil-protection strategies.

6. Theme 6: HPT Management Should Intensify Monitoring Rather Than Chemical Dependence

Drought and subsequent rainfall transitions can create changing conditions for pests and pathogens. Recovery programmes should therefore intensify pest and disease scouting, georeferenced mapping, and threshold-based interventions. Ganoderma surveillance deserves particular emphasis because disease management is difficult once advanced symptoms develop and because long plantation cycles allow inoculum and infection risk to accumulate (Murphy et al., 2021; Flood et al., 2022).

Paterson (2020, 2023) has examined possible climate interactions with basal stem rot risk in Southeast Asia. Although specific future disease patterns remain uncertain, the management implication is straightforward: climatic stress and disease risks should not be treated independently.

The role of biodiversity should also be incorporated into IPM. Understory vegetation supports arthropods and other organisms, although individual taxa may respond differently to management intensity (Hood et al., 2020; Pashkevich et al., 2022). Consequently, sanitation should focus on identifiable hazards rather than assuming that a biologically simplified plantation is automatically healthier.

7. Theme 7: Stopbund Operation Requires Hydrological Triggers

The proposal to open stopbunds once rainfall becomes stable is conceptually sound, but “stable rainfall” needs an operational definition. Opening should not be triggered simply by the first heavy storm or a predetermined September/October date.

A block-level decision should instead consider: cumulative rainfall over recent weeks; number of effective rainfall days; root-zone soil moisture; standing-water duration; drain levels; water-table depth; soil texture; slope; palm symptoms; and forecasts. The decision may be to keep a stopbund closed, partially release water, open it temporarily, or operate structures sequentially along a drainage hierarchy.

Figure 2 shows why a fixed rule such as “open all stopbunds after rain begins” is potentially inefficient. The appropriate operation changes as the system progresses from drought to recharge, recovery, and wet-season excess.



Figure 2. Adaptive Stopbund and Water-Management Decision Framework
Source: Author Synthesis Based on Akram Et Al. (2022), Warren-Thomas Et Al. (2022), Mccalmont Et Al. (2023), Asmara and Randhir (2024), and Safitri Et Al. (2026).

The larger implication is that every stopbund should eventually become part of a mapped hydrological system. Managers need to know what area each structure influences, how much water can be retained safely, where overflow moves, which blocks receive water, and what downstream consequences follow from opening.

8. Theme 8: SAP/Hydrogel Is Promising but Still Experimental for Oil Palm Cover Crops

Superabsorbent polymers can absorb substantial quantities of water and release part of the stored moisture as surrounding soil dries. Reviews and meta-analyses show that SAP can improve water productivity, soil physical properties, and crop performance, but responses depend strongly on polymer characteristics, soil conditions, application method, climate, and crop type (Ostrand et al., 2020; Saha et al., 2020; Ai et al., 2021; Zheng et al., 2023).

The global meta-analysis by Zheng et al. (2023) found positive average effects on yield and water productivity but also substantial context dependence. This means that commercially branded absorbent products should not be transferred directly into estate-wide practice without local validation.

The proposal to use Aqua Soft or a similar absorbent material for legume establishment if drought persists beyond September/October is nevertheless scientifically plausible as an experimental treatment. Amirkhani et al. (2023) demonstrated improved germination and stand establishment using SAP-coated red clover seed under water-limited conditions. Zhu et al. (2022) also provide

evidence that bio-derived hydrogel systems can improve plant performance under field conditions.

For East Kalimantan, the appropriate first step would be replicated field trials comparing untreated LCC seed, SAP-coated seed, localized SAP soil incorporation, alternative mulch-based moisture conservation, and combinations of these treatments. Outcomes should include germination percentage, establishment rate, biomass, soil moisture, polymer dose, labour requirement, cost, and persistence.

9. Theme 9: Drought-Resilient Genetics Is a Long-Term Requirement

Genetic variation in oil palm drought response is now documented at physiological, molecular, and mature-yield levels. Wang et al. (2020) identified drought-responsive genes in roots, while Nuanlaong et al. (2022) and Suraninpong et al. (2023) developed approaches for candidate-gene and molecular-marker identification related to drought tolerance.

Bayona-Rodríguez and Romero (2024) demonstrated substantial differences among cultivars across photosynthetic, water-potential, osmotic, and antioxidant variables. Montoya et al. (2024) likewise found genotype-specific differences in photosynthetic performance under drought among *Elaeis guineensis*, *E. oleifera*, and interspecific material. Mejía-Alvarado et al. (2024) integrated transcriptomic and physiological responses, strengthening understanding of the molecular basis of drought tolerance.

However, a nursery-selected drought-tolerant genotype is not automatically the most profitable commercial material. Mature-palm yield, oil extraction, disease resistance, architecture, soil adaptation, and long-term stability must also be considered. Hermanto et al. (2023) is particularly important because it shows how multiseasonal mature-palm yield records can complement nursery screening.

Therefore, the proposed concept of MTK—moderately drought-tolerant material—should be operationalized as locally validated drought-resilient planting material with high yield stability under water-limited conditions. Claims that a clone “requires minimum water but produces maximum yield” should be replaced by measurable criteria.

DISCUSSION

1 From “Post-El Niño Programme” to a Three-Phase Recovery Strategy

The strongest conclusion from the reviewed literature is that the recovery programme should not begin at a single calendar date. Rather, it should move through three states: ongoing drought stabilization, hydrological recovery, and physiological/production recovery.

Phase I: Ongoing Drought

When severe water limitation persists, priority should be given to retaining water, avoiding unnecessary drainage, protecting functional canopy area, maintaining mulch, reducing severe competition near palms where justified, and strengthening HPT surveillance. Heavy fertilizer applications should generally be deferred unless reliable rainfall and soil moisture conditions support uptake.

Organic residues can continue to be strategically applied because they contribute surface protection and longer-term soil rehabilitation. However, logistical disturbance of extremely dry soils should be minimized and fire-risk management should remain a priority.

Phase II: Hydrological Recovery

Hydrological recovery begins when rainfall becomes sufficiently frequent to recharge the rooting zone rather than merely wetting the surface. At this stage, stopbunds can be adjusted progressively, water can be redistributed toward deficient areas, and recovery fertilizer can begin in split applications.

This phase should be monitored closely because the transition can occur unevenly across topographic positions. Low areas may become wet while upper terraces remain moisture deficient. Uniform estate-wide treatment can therefore produce both waterlogging and continuing drought within the same management cycle.

Phase III: Physiological and Production Recovery

Once water availability has stabilized, attention shifts toward restoring nutritional balance, maintaining leaf area, rebuilding soil condition, monitoring reproductive recovery, and evaluating delayed yield consequences. The phase may last many months because FFB reflects reproductive events initiated earlier. **Figure 3** provides the operational core of the proposed programme. Each phase has a different limiting factor and therefore requires a different management priority.

Figure 3. Three-Phase Oil Palm Drought-Recovery Framework

Match the intervention to the dominant limiting factor in each recovery stage



Source: Author synthesis.

Figure 3. Three-Phase Oil Palm Drought-Recovery Framework

Source: Author Synthesis

The framework also prevents contradictory interventions. For example, water should not simultaneously be aggressively discharged and treated as the principal drought-recovery resource. Likewise, high fertilizer doses should not be used to solve a problem whose primary cause remains insufficient water.

2.Reassessment of the Seven Proposed Quick Wins

A. Extra Fertilization

This recommendation should be retained but renamed **targeted recovery fertilization**. The evidence strongly supports correcting nutrient deficiencies but equally strongly indicates that fertilizer response decreases when water is severely limiting (Prabowo et al., 2023; Wandri et al., 2025).

The preferred programme is therefore leaf-analysis- and block-history-based, with balanced nutrient correction and split application after moisture recovery. Potassium deserves particular attention because of its importance in oil palm productivity and its widespread deficiency in Indonesian systems (Sugianto et al., 2023; Lim et al., 2023).

B. Consistent JJK/EFB, Compost and LA Application

This intervention is strongly supported. It should be considered both a fertility practice and a long-term drought-resilience measure. EFB and frond residues increase organic inputs and can improve carbon pools, nutrient cycling, microbial activity, and physical soil conditions (Formaglio et al., 2021; Noiro et al., 2022).

Consistency matters because soil organic matter accumulates gradually. Residue recycling should therefore continue beyond the immediate El Niño recovery period.

C. HPT Mitigation

This recommendation is also retained, but the emphasis should be on surveillance, mapping, early detection, biological functions, and threshold-based IPM. Climatic stress should trigger more frequent scouting rather than automatic pesticide escalation (Murphy et al., 2021; Flood et al., 2022).

D. Opening Stopbunds after Rainfall Stabilizes

The principle is appropriate, but stabilization must be measured. A combination of rainfall, root-zone soil moisture, drain level, water table, topography, and forecast information should determine opening. Progressive or partial opening will often be more rational than simultaneous full release.

E. Slashing GCC/Nephrolepis

Selective slashing is preferable to broad elimination. Live biomass can be reduced where water competition or sanitation requires it, while slashed material can remain as protective mulch. Useful cover should be retained where it contributes soil protection without substantial palm competition (Yahya et al., 2022; Thoumazeau et al., 2024).

F. Maintaining Frond Management

This should remain a core practice. Over-pruning drought-stressed palms can reduce photosynthetic recovery, while organized frond placement provides organic matter and biological benefits. Harvesting requirements and disease sanitation still need to be respected.

G. Aqua Soft/SAP for Legume Establishment

This recommendation should move forward as a field experiment rather than automatic commercial deployment. The broader SAP literature is promising, particularly under rainfed and water-limited conditions, but mature oil palm plantation evidence remains inadequate (Saha et al., 2020; Zheng et al., 2023; Amirkhani et al., 2023).

3. Long-Term Water Management: Retain, Harvest, Redistribute and Drain

The first long-term proposal – integrated water management – is arguably the most important structural response. Plantation water infrastructure should be capable of performing four functions.

The integrated water-management system comprises four linked functions. Retention keeps rainfall within the landscape long enough to support infiltration and root-zone recharge. Harvesting transfers a portion of excess wet-season water into designated storage such as retention ponds, reservoirs, controlled drains, or other site-appropriate structures. Redistribution enables stored or retained water to benefit blocks experiencing deficit where gravity, pumping systems, canal design, and environmental requirements allow. Drainage protects the plantation when rainfall exceeds soil and storage capacity, thereby completing a system that must operate across both drought and wet-season conditions.

Figure 4 demonstrates that water-management infrastructure cannot deliver resilience independently. Water retention becomes more effective when soils have sufficient organic matter and cover; restored soil moisture produces greater benefits when nutrient balance is adequate; and genetic tolerance cannot compensate indefinitely for structurally poor hydrology.

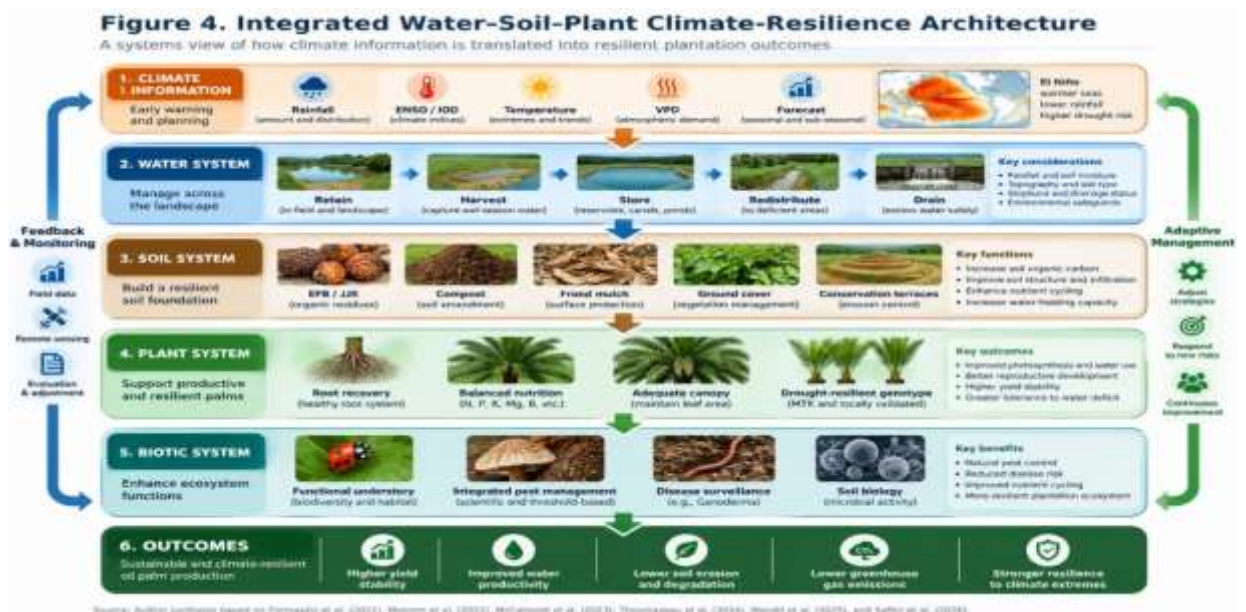


Figure 4. Integrated Water-Soil-Plant Climate-Resilience Architecture
Source: Author synthesis based on Formaglio et al. (2021), Monzon et al. (2022), McCalmont et al. (2023), Thaumazeau et al. (2024), Wandri et al. (2025), and Safitri et al. (2026)

This systems perspective is especially important because future climate resilience will require management of both drought and excessive rainfall. A plantation designed only to remove water may become vulnerable during El Niño, while a plantation designed only to retain water may suffer during intense wet-season rainfall. Adaptive infrastructure must do both.

4. Peat and Mineral Soils Require Different Rules

A major limitation of generalized recommendations is variation in soil hydrology. On mineral soils, drought management often focuses on infiltration, soil-water storage, runoff reduction, and redistribution. On peat, water-table depth has additional implications for oxidation, subsidence, fire risk, greenhouse-gas emissions, root-zone aeration, and productivity.

Warren-Thomas et al. (2022) found no simple yield-biodiversity trade-off across the observed water-table gradient in peatland smallholdings, while McCalmont et al. (2023) suggested that shallower water tables may improve climatic resilience while reducing peat carbon emissions without necessarily compromising photosynthetic performance. Dhandapani et al. (2022), Swails et al. (2021), and Nishina et al. (2023) further demonstrate the complex greenhouse-gas and biogeochemical consequences of peat drainage.

Therefore, a single “open stopbund” SOP for both mineral and peat fields is scientifically inappropriate. Peat requires water-table targets and environmental safeguards specifically designed for peat hydrology.

5. Conservation Terraces at Replanting

The proposed creation of conservation terraces during replanting is strategically strong because replanting is one of the few times when large-scale physical redesign can occur without disrupting an existing mature stand. This window allows contouring, drainage, retention structures, road-water interfaces, and ground-cover establishment to be designed as a coordinated system rather than retrofitted after canopy closure.

Terraces should be designed according to slope, soil erodibility, rainfall intensity, machinery requirements, drainage pathways, and planting geometry. The objective is not simply to create flat planting positions but to slow runoff, increase infiltration, retain organic residues, and prevent erosive concentration of water.

Erosion studies in oil palm landscapes demonstrate that changes in land cover and surface management can substantially influence runoff and soil loss (Jaya et al., 2023). Watershed modelling similarly shows that oil palm landscapes influence downstream water quantity, sediment, and nutrient movement (Asmara and Randhir, 2024).

Conservation terraces should therefore be integrated with cover-crop establishment, EFB or frond placement, correctly designed culverts and drains, road-water management, and retention structures. A terrace built without safe overflow pathways can simply transfer erosion from one point to another.

6. Drought-Resilient Planting Materials

Long-term resilience should incorporate genetic improvement, but genetic claims require discipline. Bayona-Rodríguez and Romero (2024) identified physiological traits useful for discriminating drought responses, including photosynthesis, predawn water potential, transpiration, osmotic indicators, and

antioxidant responses. Montoya et al. (2024) documented genotype variation in photosynthetic behaviour. Suraninpong et al. (2023) showed the potential of molecular markers associated with drought response.

These advances make drought-resilient planting material increasingly realistic. Nevertheless, commercial deployment should be based on multi-environment trials that measure FFB, oil yield, bunch number, bunch weight, drought-year stability, disease resistance, and long-term economic performance. The most useful operational definition of MTK is therefore not “minimum water requirement” but **a planting material demonstrating smaller yield penalties and acceptable recovery under defined water-deficit conditions while maintaining competitive long-term oil productivity**. Selection criteria should therefore combine drought-year yield stability with oil yield, disease resistance, recovery rate, and performance across representative soil and hydrological environments.

7. Proposed Estate Monitoring Dashboard

An integrated drought-recovery strategy requires measurements that can trigger decisions. At minimum, the following groups of indicators should be considered.

Climate monitoring should include daily rainfall, consecutive dry days, temperature, relative humidity, and derived VPD. Seasonal ENSO and IOD outlooks can provide broader risk context.

Hydrological monitoring should include representative root-zone soil moisture, drain water levels, retention-pond volume, water-table depth on peat, and the status of stopbunds and culverts. Plant monitoring should complement these measurements through visual drought scoring, functional frond number, spear development, leaf nutrient analysis, bunch number, bunch failure, and FFB production. Together, these indicators distinguish water limitation from nutritional or canopy constraints and provide leading signals before yield responses become fully visible.

Soil monitoring should include pH, organic carbon, K, Mg and other relevant nutrients, bulk density where compaction is suspected, infiltration, and soil moisture. HPT monitoring should simultaneously record Ganoderma incidence, defoliator populations, rodent damage, beneficial organisms, and emerging block-specific problems. Integrating these measurements transforms the programme from a static list of recommended practices into an adaptive management system in which interventions are triggered by observed conditions and evaluated over time.

8. Research Agenda for East Kalimantan

Several elements of the proposed strategy require local experimentation. The highest priority would be a factorial or strip-trial programme comparing fertilizer timing under different soil-moisture conditions. Such trials could determine whether post-drought split fertilization improves nutrient recovery and FFB relative to conventional timing.

A second priority is stopbund experimentation. Blocks could be monitored under contrasting release thresholds, using soil moisture, drain levels,

palm water status, and subsequent productivity to identify better operating rules.

Third, commercial SAP products proposed for LCC establishment should undergo replicated comparison with untreated seed, mulch-based establishment, and different SAP rates. Cost per successfully established hectare should be calculated alongside agronomic response.

Fourth, vegetation trials should compare complete clearing, selective slashing, managed *Nephrolepis* or other functional understory, and conventional business-as-usual management. Outcomes should include palm yield, soil moisture, infiltration, soil structure, erosion, labour cost, HPT, and biodiversity indicators.

Finally, future replanting blocks should provide long-term testing sites for drought-resilient planting material. The strongest programme would pair genetic treatments with hydrological monitoring so that genotype $\times$ environment interactions can be quantified.

CONCLUSIONS AND RECOMMENDATIONS

Prolonged El Niño drought should be treated as a multi-stage disturbance rather than a temporary shortage of rainfall. Water deficit alters oil palm photosynthesis, root function, nutrient uptake, reproductive processes, and subsequent FFB formation, creating production effects that can persist well beyond the return of rain. Consequently, an effective recovery programme must distinguish ongoing drought, hydrological recovery, and physiological or production recovery.

The proposed quick-win programme is broadly supported after several important refinements. Additional fertilizer should become diagnosis-based, balanced, and split recovery fertilization implemented after root-zone moisture becomes adequate. JJK/EFB, compost, suitable land-applied organic material, and frond recycling should be maintained consistently because they contribute not only nutrients but also soil organic carbon, biological activity, surface protection, and hydrological buffering. HPT management should emphasize intensified monitoring and IPM. Stopbunds should be regulated according to actual hydrological indicators. GCC and *Nephrolepis* management should prioritize selective slashing and retention of useful biomass rather than indiscriminate vegetation elimination. Frond management should protect adequate canopy function while returning residues to the soil. Superabsorbent polymers may assist cover-crop establishment under persistent dry conditions, but their use should initially remain experimental and evidence-driven.

Long-term resilience requires a more fundamental transition. Water management needs to become an integrated system capable of retaining, harvesting, storing, redistributing, and safely draining water. Conservation terraces and associated soil-water infrastructure should be incorporated during replanting wherever topography justifies them. Soil organic matter should be treated as biological water infrastructure, while drought-resilient planting materials should be validated through mature-palm, multi-environment trials rather than selected solely through nursery observations.

The principal management lesson is therefore that drought recovery should begin with the water-soil-root continuum rather than fertilizer alone. Once water has genuinely returned to the rooting zone, nutrition, canopy, organic matter, vegetation, and reproductive recovery can be managed more effectively. By integrating these interventions with hydrological infrastructure and drought-resilient genetics, oil palm estates in East Kalimantan can progress from reactive El Niño mitigation toward adaptive climate-resilient production.

FURTHER STUDY

This research still has limitations, so further studies are needed on the topic From El Niño Drought Recovery to Climate Resilience: An Integrated Water-Soil-Plant Management Framework for Oil Palm Plantations to refine this study and add insights for both the authors and readers

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