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Beyond Conventional Fertilization: Assessing the Agronomic, Technical, Economic and Environmental Feasibility of Fertigation in Indonesian Oil Palm Plantations

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Abstract

Fertigation combines irrigation and nutrient delivery, but the feasibility of adopting it in Indonesia's heterogeneous oil palm sector cannot be inferred from cross-crop performance claims. This qualitative literature review synthesises peer-reviewed studies published between 2020 and October 2026 to assess agronomic, technical, financial, environmental and institutional conditions for adoption. It distinguishes direct oil palm findings from transferable fertigation and irrigation engineering evidence and introduces a counterfactual framework separating better conventional fertilisation, irrigation alone and integrated fertigation. Studies demonstrate major nutrient deficiencies in Indonesian smallholder plantations and show that moisture stress influences yield; nevertheless, the available literature does not establish a reliable Indonesia-wide incremental fertigation yield response or investment return. Potentially favourable settings comprise existing mineral-soil blocks with recurrent, economically significant dry-season water limitations, secure water access, treatable water quality, measurable nutrient-delivery constraints and competent maintenance. Important risks include emitter clogging, water abstraction, underestimated lifecycle operating expenses, weak comparative evidence and unsuitable implementation on sensitive peatlands. A gated feasibility procedure and replicated multi-treatment pilot protocol are proposed, supported by lifecycle net-present-value and environmental indicators. The review concludes that investment should follow documented site-specific additionality rather than generalised assumptions that precision input delivery is superior. Initial priority in many settings remains balanced nutrition, soil conservation and reliable agronomic management.

Keywords: Oil Palm, Fertigation, Indonesia, Drip Irrigation, Water Productivity, Nutrient-Use Efficiency, Capital Budgeting, Climate Resilience, Sustainable Intensification, Smallholder Adoption.

Introduction

Indonesia's oil palm industry faces a productivity problem that cannot be solved by treating all plantation landscapes as agronomically uniform. Mature plantations differ in rainfall seasonality, soil water storage, planting material, access to infrastructure, and the quality of day-to-day management. These differences matter because the economic return to an additional litre of irrigation water or kilogram of dissolved fertiliser depends on the limiting factor at a particular location. Large observational analyses of Indonesian smallholders find material gaps between attainable and realised fresh fruit bunch yields, while long-term work with well-managed estates identifies drought and atmospheric demand as important contributors to yield fluctuations. Together, these findings motivate a location-specific examination of integrated water and nutrient management rather than an assumption that technology intensification is invariably productive [1-3]. Fertigation denotes the intentional application of dissolved or suspended, technically suitable nutrients through an irrigation distribution system. It therefore entails more than placing fertiliser in a water tank: reliable hydraulic delivery, filtration, fertiliser compatibility, root-zone targeting and monitoring are necessary to translate a prescription into a uniform field dose.

For Indonesian oil palm, there are three conceptually distinct interventions: upgrading fertiliser recommendation and placement without irrigation; providing irrigation while retaining separate fertiliser application; and installing a system capable of jointly scheduling irrigation and nutrient injection. Failure to distinguish these interventions leads to misleading comparisons in which the benefits of water supply or correcting an existing nutrient deficit are wrongly attributed to fertigation itself [4-6]. An urgent issue is the difference between technological potential and a feasible investment. Estate operators may be able to mobilise pressurised networks, fertigation tanks and technically qualified staff across adjacent blocks, but they still need to establish that additional crop revenue or verifiable resource savings justify equipment, pumping, maintenance and replacement costs. Independent smallholders often face a prior problem: insufficient fertiliser purchases, inappropriate nutrient balance, limited working capital and dependence on local input

and credit networks. Introducing a capital-intensive delivery technology before resolving these constraints could divert scarce funds from more effective management practices. The review consequently defines feasibility as a conjunction of agronomic relevance, engineering reliability, economic additionality, environmental acceptability and implementational capacity [7-9].

Interest in fertigation has been stimulated by controlled experiments and synthesis studies involving annual crops, vegetables and other plantation crops. Those studies commonly report higher resource productivity when fertiliser and water placement are synchronised, although responses vary by crop, irrigation baseline, fertiliser rate and soil conditions. A long-term coconut trial is suggestive because it involves a perennial palm, yet its responses cannot be transplanted numerically to Elaeis guineensis. The oil palm literature also documents responses to irrigation and NPK supply, but does not yet provide a sufficient body of replicated Indonesian mature-palm trials that isolates combined fertigation effects over a full yield-response horizon. This contrast between persuasive mechanisms and limited locally decisive evidence is the foundation of the present review [4,10-12]. The research questions are therefore both explanatory and decision-oriented. Under what environments does simultaneous delivery of water and soluble nutrients solve a binding production constraint? Which forms of distribution infrastructure are robust enough for tropical plantation conditions? When do incremental gains exceed discounted total lifecycle costs, and what environmental safeguards should act as hard constraints rather than monetisable afterthoughts? The review asks how these answers should differ among mineral-soil estates, water-limited blocks, topographically difficult sites, smallholder groups and peatland holdings. It also seeks to identify the kind of field evidence that would be required before moving from demonstration to commercial scale [13-15].

The manuscript offers three contributions. First, it distinguishes direct oil palm observations from cross-crop fertigation studies and from proposed design criteria, preventing the transfer of context-specific effect sizes as if they were Indonesian oil palm forecasts. Second, it develops a sequential screening model in which water entitlement, soil and crop need, technical reliability, net present value, and environmental risk are considered before any large investment decision. Third, it presents a comparative pilot protocol and a structured agenda for estate managers, researchers, suppliers and public institutions. This turns a qualitative synthesis into a falsifiable decision framework rather than a generalised endorsement of a particular piece of equipment [16-18].

Literature Review: Concepts and Theoretical Foundations

The first theoretical foundation is resource co-limitation. Crop production is constrained by the interacting availability of water, plant nutrients, radiation and biological capacity, so reducing one limitation can increase responsiveness to another. In oil palm, fertiliser may improve attainable production in favourable weather while offering limited protection against episodes of severe water stress. A multi-year Indonesian analysis showed considerably higher average yields under improved nutrient supply, but little mitigation of low-yield cycles caused by water limitation. It follows that nutrient and water treatments must be assessed factorially where possible: a significant fertiliser response under irrigation is not proof that injection through the irrigation line is the necessary or least-cost delivery method [2,4,19]. The second foundation is the spatial and temporal matching of supply with demand. Conventional fertiliser granules are often applied in discrete events, exposed to local moisture patterns, microbial transformations and transport by runoff or percolation. Fertigation theoretically offers frequent, smaller nutrient doses within the wetting zone, provided that the relevant active roots occupy that zone and the emitter network functions uniformly. The apparent promise is greatest when dose timing avoids vulnerable hydrological periods, rather than merely increasing the number of applications. Nutrient uptake requirements for oil palm are large and vary with yield, nutrient harvest removal and palm growth; prescription should therefore begin from measured tissue status and realistic yield targets, not from a fixed universal injection recipe [7,20,21]. The third foundation is water-limited yield and climate resilience. Oil palm exhibits delayed reproductive consequences of moisture shortages because stress affects inflorescence development, abortion and sex differentiation before visible changes occur in harvested bunches. Indonesian data associate yield variations with soil-water deficit and vapour pressure deficit; cultivar studies further indicate heterogeneity in response.

Consequently, a trial designed for only one dry season may underestimate or misallocate benefits, and improvements in irrigation water productivity cannot be equated with improved basin-level water security. Irrigation may preserve a production opportunity where rainfall is unreliable, but its justification depends on dependable abstraction during precisely the periods when competing users may also experience scarcity [22-25]. Water requirements must be inferred from a defensible local water balance rather than generic annual rainfall thresholds alone. Sap-flow measurements and plantation-scale hydrological modelling reveal that solar radiation, atmospheric demand, soil properties and management alter transpiration and catchment responses. Reports on dry Malaysian oil palm areas provide useful irrigation precedents, but an Indonesian design needs local measurements of daily demand, effective rainfall, soil water-holding capacity, topographic redistribution, groundwater interactions and storage reliability.

Soil-specific analyses from Central Kalimantan underscore that identical rainfall deficits can have different yield consequences on different soil classes, which makes blanket prescriptions of litres per palm per day inappropriate for feasibility studies [13,14,26,27]. Instrument-based monitoring in Indonesian oil palm plantations has additionally identified differing moisture regimes on Ultisols and Spodosols, including plots where hardpan-breaking and mounding treatments altered the soil context. These observations reinforce the importance of measuring soil moisture at multiple depths rather than relying exclusively on rainfall records. Because the reported sensor data describe particular locations, they inform site diagnosis and instrument selection rather than a universal irrigation trigger [28].

Figure 1 Integrates the Core Theoretical Dimensions Considered in This Review, Locating Technology Choice Between Biophysical and Institutional Preconditions on One Side and Economic, Agronomic and Environmental Outcomes on the Other. These Factors Operate as Interdependent Screening Conditions, Rather Than Compensatory Scores that Can Be Summed to Justify an Otherwise Unsuitable Site.

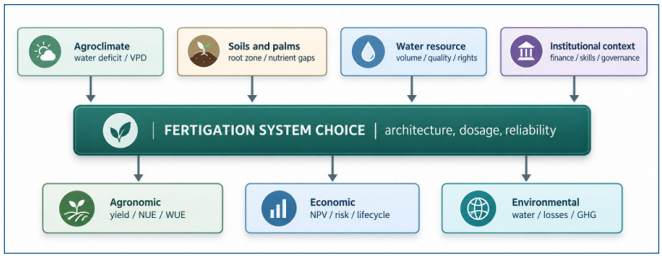


Figure 1: Multidimensional Feasibility Logic for Fertigation on Existing Indonesian Oil Palm Land (Original Conceptual Synthesis; No Empirical Effect Sizes Implied).

As Figure 1 indicates, the feasibility categories are interdependent rather than interchangeable. A nominal increase in fertiliser efficiency is not enough to establish a viable investment when dry-season water rights, system reliability or lifecycle cash flow remain unresolved. The diagram functions as an analytical organising model, not as statistical evidence of causal effects. An important distinction concerns fertiliser-use efficiency, nutrient-use efficiency and water productivity. Agronomic efficiency describes additional crop output per unit of nutrient applied above a control; recovery efficiency concerns additional nutrient uptake; partial factor productivity compares total output with total nutrient input; and irrigation water productivity compares incremental output with irrigation water consumed.
These measures answer different questions and may move in different directions. A technology can improve apparent efficiency by lowering dosage while allowing a nutrient deficiency to persist, or can increase crop production at the expense of higher groundwater extraction. Comparable baselines and explicit numerators, denominators and measurement periods are therefore prerequisites for valid performance claims [12,29,30].

The fourth foundation is engineering reliability. Fertigation depends on hydraulics: pump sizing, distribution losses, pressure variation, emitter discharge and the performance of valves and injection hardware. A nominally precise system becomes imprecise if part of its network clogs or if fertiliser precipitation alters emitter flow. Experimental studies identify interactions among suspended sediment, calcium and magnesium chemistry, microbial growth and phosphorus sources, while long-running subsurface systems show that nominal flow uniformity can deteriorate over several years. These findings translate into a need for pre-installation source-water analysis, controlled fertiliser compatibility tests, emergency flushing procedures, hydraulic audits and recurrent capital replacement provisions [6,31-33]. Fertiliser chemistry adds a separate layer of design risk. Solubility changes with temperature, concentration, water hardness and mixing order; a fertiliser suitable for broadcasting may be unsuitable for injection. Studies of phosphorus fertigation show that source formulation and application frequency affect availability, whereas experiments involving sediment-laden or brackish water demonstrate that inappropriate nutrient combinations can aggravate deposition inside emitters.

No assumption should be made that every conventional Indonesian NPK blend is safely soluble or compatible with a selected irrigation network. Operational protocols must include jar tests, pH and electrical conductivity monitoring, source segregation when required, backflow prevention and manufacturer-supported cleaning and maintenance procedures [21,34-36]. The fifth foundation is incremental capital budgeting. A feasibility analysis must evaluate additional net cash flows relative to the best realistic alternative, not compare a fully equipped fertigation estate against an intentionally neglected control. Incremental revenue may originate from changed yield, bunch quality or seasonal stability; savings may come from fertiliser, labour or loss prevention. Offset these against pump electricity or diesel, infrastructure depreciation, skilled technicians, filtration media, treatment chemicals, repair and replacement, water fees, insurance, theft and damage risk, and potential foregone environmental services. Discounted appraisal should consider the duration of the equipment and biological response, which often differ, and should explicitly account for price variability and possible years of poor performance [9,10,18]. The sixth foundation is sustainable intensification and institutional fit. Raising yield per hectare may relieve pressure for expansion under certain market and governance conditions, but this result is not automatic; profit increases can also create incentives for further investment and land conversion. For independent smallholders, unequal credit access, transaction costs, maintenance coordination and information gaps may dominate the engineering question.Research on Indonesian fertiliser decisions describes widespread financial constraints, irregular purchases and the importance of informal or group-linked credit.

This points toward a hierarchy in which diagnosis, balanced nutrition and field management precede expensive infrastructure, while cooperative sharing is considered only when governance and service arrangements are dependable [1,8,9,37]. A recent Malaysian trial with immature palms on sloping terrain found that a controlled-release fertiliser treatment could maintain early establishment performance relative to conventional split applications. This provides a credible non-fertigation alternative to evaluate where terrain or logistics complicate fertiliser delivery, but its first-year vegetative outcomes should not be interpreted as mature-palm fresh fruit bunch effects [38]. A field-based Indonesian smallholder study offers further evidence that the realistic comparator for fertigation includes soil stewardship rather than fertiliser application alone. Potassium fertilisation was associated with palm performance, while maintained understorey vegetation was positively related to soil-structure indicators.

The results support testing an integrated low-capital management package as a competing intervention, although the observational setting does not establish a national causal yield response [39].

Environmental evaluation must also account for nitrogen transformations and the hydrological setting. The potential advantage of a smaller, more frequent nutrient dose is lower local nutrient surpluses or reduced losses, but the magnitude and direction depend on timing, microbial activity, wetting patterns and soil aeration. Meta-analysis from Chinese agricultural systems reports reductions in some reactive nitrogen loss pathways under drip fertigation, yet Indonesian oil palm plantation flux studies show that emissions are temporally variable and sensitive to fertiliser events. These lines of evidence justify monitoring rather than a presumption of environmental benefit. They also warn against presenting results from annual, often temperate crops as tropical perennial plantation emission factors [30,40-42]. A 2025 dryland agricultural meta-analysis likewise attributed changes in greenhouse gas fluxes partly to drip-irrigation effects on soil

water-filled pore space, with different responses for individual gases. This mechanistic evidence strengthens the case for measuring net emissions at oil palm sites rather than assuming that more efficient irrigation produces universal mitigation [43]. Transferable irrigation-model evidence also cautions against assuming that the uniformity of applied liquid directly equals uniformity of nutrients accessible in the soil profile. In a 2025 simulation supported by soil-tank measurements, the timing and spatial distribution of sprinkler fertigation influenced soil nitrogen patterns and potential nitrate movement.

The model was not built for Indonesian oil palm and does not quantify local leaching reductions, but it supports pairing emitter measurements with root-zone solute and drainage observations when comparing technologies [44]. Peatlands warrant a separate conceptual treatment because land drainage, subsidence and greenhouse gas dynamics are not solved by adding an irrigation network. Research from Indonesian and Malaysian peat landscapes has examined rewetting, water-table management and the photosynthetic response to shallower drainage. These studies concern the fundamental carbon and hydrological governance of peat soils, not proof of fertigation benefits. Accordingly, peat should not be treated as another inexpensive candidate site merely because canals are present. Any intervention must be consistent with applicable peat protection, water-table requirements, wildfire prevention and broader restoration objectives; potential fertigation gains cannot be used to justify environmentally harmful drainage or expansion [45-48].

Methodology: Qualitative Literature Review

This study uses a qualitative literature review, not a systematic literature review and not a meta-analysis. Its purpose is to interpret mechanisms, contextual conditions, conflicting empirical observations and implementation trade-offs across disciplinary fields. The approach is appropriate because the direct Indonesian oil palm fertigation evidence is sparse relative to the heterogeneous evidence available on oil palm irrigation, mineral nutrition, precision agricultural engineering, farm economics and environmental outcomes. A rigid pooled effect-size estimate would risk an unjustified level of comparability. In contrast, interpretive synthesis allows explicit examination of why a finding obtained in a greenhouse, an annual cereal crop or a Malaysian estate does not directly identify a commercially achievable effect in an Indonesian mature oil palm block [4,5,16]. The principal publication window is January 2020 to October 2026, with academic journal articles selected from agricultural water management, agronomy, crop physiology, hydrology, tropical sustainability, environmental science, and socio-economic development literature. Candidate material was identified through targeted title and topical searches in publisher repositories and scholarly indexing sources, using combinations of oil palm, Elaeis guineensis, Indonesia, irrigation, fertigation, drip, nutrient balance, water stress, evapotranspiration, yield gap, phosphorus, emitter clogging, greenhouse gas, cost and adoption. Preference was given to traceable journal records with DOIs and directly accessible article or abstract pages. The review does not claim comprehensive database capture or exhaustive screening numbers [1,4,49].

Studies were appraised by crop specificity, geographic relevance, design strength, duration, comparability of controls, measured outcomes, operational conditions and obvious sources of confounding. Direct evidence included field work on oil palm nutrition, irrigation response, climate constraints and hydrology in Indonesia and nearby Southeast Asian settings. Mechanism-level transferable evidence comprised cross-crop fertigation experiments, engineering studies and published synthesis studies. Illustrative calculations and system diagrams developed in this review were classified separately as proposed analytical tools. Wherever possible, intervention descriptions were inspected to avoid interpreting a study of irrigated palms receiving separately applied fertiliser as an experiment that identified the causal effect of fertigation [10,11,19]. A three-level evidence coding convention was adopted. Class A describes direct oil palm evidence relevant to the Indonesian implementation context, albeit not necessarily a fertigation trial; Class B describes supporting regional perennial-crop or plantation evidence; and Class C describes broader cross-crop and engineering transfer.

A fourth category, analytical proposal, covers decision rules and monitoring indicators constructed for this review rather than empirically validated. Findings were interpreted thematically across water demand, nutrient supply, hydraulic delivery, financial additionality, environmental impacts and adoption conditions. This classification avoids giving a single pooled credibility score to studies measuring fundamentally different outcomes [14,20,34]. The synthesis emphasised negative cases and counterfactual comparisons. If balanced broadcast fertiliser applications improve growth, they demonstrate that nutrient limitation exists but do not prove fertigation is needed. If irrigation improves dry-season production, that supports the value of water supply but not necessarily nutrient injection.

If an emitter network improves delivery uniformity under laboratory conditions, the field-scale conclusion still depends on water quality, staff capacity and long-term uptime. These checks informed a practical comparison structure with four treatments: current practice, optimised conventional nutrient management, optimised management plus irrigation without injection, and complete fertigation. Financial interpretation then asks about the incremental effect of the final step, not the total improvement over a deficient baseline [4,7,33]. Table 1 provides the comparative structure needed to isolate the incremental effect of fertiliser injection from improved conventional nutrition and water-only irrigation. Specifically, the matched comparison between T2 and T3 tests whether fertiliser injection itself offers an advantage once water supply and total nutrient inputs are held constant.

Table 1: Proposed Four-Treatment Comparison and Identifying Contrast.

Code	Field Treatment	Interpretive Contrast
T0	Current practice	Existing operational baseline
T1	Optimised conventional fertiliser, rainfed	Basic nutrient-management gain vs T0
T2	T1 plus irrigation, fertiliser applied separately	Incremental effect of irrigation vs T1
T3	Fertigation with matched nutrient and water input	Injection and scheduling additionality vs T2

Table 1 is a trial design proposal rather than the description of an already completed Indonesian experiment. Matched

nutrient and water doses in T2 and T3 are particularly important for preventing fertiliser quantity or irrigation volume from confounding comparisons of delivery methods. However, the T3–T2 contrast estimates the bundled effect of injection-based placement and timing, not the mechanical act of injection in isolation. Differences in nutrient form and concentration should be recorded and, where feasible, experimentally controlled. Interpretive limitations are substantial. Publication bias may favour successful demonstrations, national and site conditions differ, and field trials may under-report maintenance failures, land-use consequences or local water competition. Moreover, many agronomic effects occur after delays attributable to oil palm reproductive development, making short observation windows poor tests of mature-palm returns. The literature also changes over time, and some journal records are published online before they appear in a paginated issue; DOI-based traceability is consequently prioritised. This manuscript is an evidence-informed feasibility synthesis, not a project-level engineering design, regulatory opinion or substitute for field hydrology and financial due diligence [22,25,50].

Results: Thematic Findings

Theme 1 concerns a compelling need for better nutrition, but not necessarily a compelling case for pipes. Detailed sampling of Indonesian independent smallholders shows that widespread deficiencies and unbalanced nutrient inputs are associated with substantial yield gaps. A separate nutrient balance study found that fertiliser was applied in only about half of the surveyed fields and that nutrient rates were particularly low relative to crop removal for potassium and magnesium. Poor placement and limited splitting also matter.

These results make nutrient diagnosis, appropriate fertiliser sources and timing a high-priority intervention. They do not establish that soluble fertilisers delivered through drip lines will outperform affordable, well-executed conventional programmes after accounting for all associated costs [3,7,20]. Yield-gap research provides an important test of the optimisation baseline. Survey and crop modelling across nearly one thousand independent smallholder fields estimated substantial differences between realised and attainable production, with nutrition, harvesting, weed management and pruning all contributing. Subsequent fieldwork documented meaningful improvements in yield and profit under better management packages, without a demonstrated requirement for fertigation infrastructure. Because improved routine agronomy can already capture part of the gap, feasibility models that ascribe the entire yield gap to fertigation would systematically exaggerate revenue. Conversely, an estate with already effective fertiliser placement and high nutrient sufficiency may have only a small incremental response to more frequent dosing, even where irrigation itself is valuable [1,9,37].

Theme 2 addresses the interaction between water and nutrients. An irrigated oil palm NPK experiment on clayey Malaysian soil reported approximately 17.3% higher fresh fruit bunch production for complete NPK treatments relative to an unfertilised comparison within an already irrigated trial. The study is valuable evidence that nutrition remains important under irrigation; it is not an experimental estimate of the difference between soluble injection and conventional fertilisation on otherwise identical irrigated plots. Indonesian long-term fertilisation trials further show that improved nutrition increased production in favourable conditions but afforded limited protection against water-related low-yield episodes. These observations favour interventions that explicitly correct the binding stress rather than assuming a mechanical synergy of water and nutrient delivery [4,9]. Theme 3 relates to climate and site selection. A large Indonesian plantation dataset connected yield fluctuations to water deficits and vapour pressure deficit, while Central Kalimantan observations identified soil-dependent drought responses across several soil classes. Sap-flow measurements illustrate sensitivity to radiation and atmospheric demand, and Indonesian site-level analyses highlight the importance of vapour pressure deficit as distinct from total rainfall. The strongest agronomic case for irrigation-assisted fertilisation is therefore likely to occur on existing mineral-soil blocks with recurrent, consequential moisture shortages, sufficient available water in the dry season and a measurable nutrient limitation. An estate in a high-rainfall zone with reliable soil moisture may gain little from additional water distribution but could still benefit from better fertiliser logistics [2,13,24,26].

Recent ENSO-based regional research strengthens the interpretation that variability in atmospheric and water-storage drivers matters to candidate screening, but does not itself predict the return on an irrigation network [51]. Theme 4 concerns the timescale of measured benefit. Oil palm reproduction and yield formation involve sensitive periods that extend well before fruit harvesting, so a sudden change in water supply cannot always be evaluated from a single short harvest series. Multi-seasonal data show that drought tolerance and yield responses differ among planting materials, while climate-review evidence identifies numerous physiological channels through which water deficits suppress productivity. An informative plantation trial should measure soil moisture and tissue nutrients immediately, vegetative responses over intermediate intervals and bunch yield through subsequent reproductive cycles. The requirement for prolonged observation increases research costs but is central to avoiding false positives caused by favourable rainfall, endogenous yield cycles or systematic differences among treatment blocks [22,23,25,52]. Theme 5 assesses evidence from other crops. A meta-analysis of Chinese agricultural systems reported an average crop-yield improvement of roughly 9.8% under drip fertigation compared with traditional irrigation and fertilisation, accompanied by reductions in several reactive nitrogen losses. A separate global synthesis of mostly annual crops also found positive average outcomes for yield and nutrient or water productivity, and one analysis of integrated water-fertiliser drip systems reported higher mean water-use and nitrogen-use efficiency.

These results support plausible mechanisms and help specify what to measure. Their numerical effect sizes, however, cannot be directly applied to mature Indonesian oil palm because crop geometry, climate, soil, plantation lifetime and baseline management differ [5,12,30]. A coconut field experiment offers a useful but imperfect perennial comparison. Its reported responses to lower fertiliser doses delivered by drip depended on baseline conventional practice and local agronomic circumstances. This supports studying whether modest and frequent nutrient doses can avoid losses, but it does not demonstrate that a palm plantation in a humid Indonesian landscape should automatically reduce fertiliser inputs by a prescribed percentage. Studies with cotton similarly show complex water-by-fertiliser response surfaces: maximum output and maximum efficiency are not necessarily achieved at the same treatment level. Thus, a commercial design

must seek the dose that satisfies oil palm nutrient requirements while minimising marginal cost and impact, rather than borrowing an annual-crop recommendation [10,11,20].

Theme 6 concerns physical system design. A basic fertigation network requires legal access to sufficient water, a storage or abstraction arrangement, pumping, pre-treatment, main and sub-main piping, pressure control, zonal isolation, a calibrated injector and emitters selected for hydraulic and agronomic properties. Its distribution uniformity depends upon pipe sizing, elevation, distance and degradation over time. Pressure-compensating emitters may simplify variable-terrain operation but can be more costly; subsurface installations may protect pipes from surface disturbance but complicate inspection and repairs. Engineering feasibility cannot be inferred merely from the availability of irrigation equipment. A block-level hydraulic specification, realistic field layout and serviceability plan are needed before any estimate of capital cost [16,33,49]. The practical delivery chain depicted in Figure 2 clarifies why fertigation is an integrated engineering system rather than a single method of fertiliser placement. Each link introduces distinct specifications and potential failure points that must be verified under site water-quality and operating conditions.

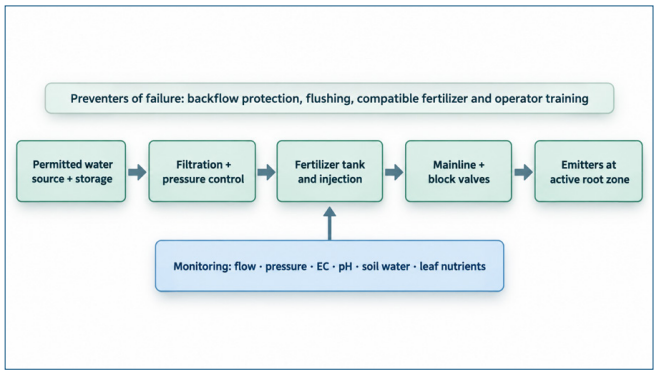


Figure 2: Illustrative Fertigation Component Chain and Operational Monitoring Requirements (Original Technical Schematic; Not an Engineering Drawing).

Figure 2 also distinguishes water and fertiliser hardware from the monitoring loop. Flow and pressure measurements establish actual delivery, whereas electrical conductivity and pH checks help detect dosing or compatibility faults; no sensor can ensure success without calibration, flushing, operator training and appropriate agronomic prescriptions. Theme 7 is water chemistry and clogging. Experimental work repeatedly identifies sediment, dissolved ions, fertiliser compounds and biofilms as interacting causes of discharge variability. Phosphorus formulations can be particularly vulnerable to precipitation under unfavourable water chemistry, while studies with brackish or highly sedimented water reveal that the effect of a given fertiliser on clogging depends on the chemistry and particles already present. Recent multi-year performance assessments further demonstrate that maintenance outcomes and system age affect discharge. For tropical plantations where source water may be turbid after storms and repair logistics difficult, filtration and cleaning should be modelled as recurring operational expenditures rather than optional accessories [6,31-33].

A practical water-quality protocol would test suspended solids, turbidity, pH, hardness, salinity, biological contamination and relevant dissolved ions across wet and dry seasons. Manufacturer-specific fertiliser compatibility tests should then establish a safe range of injection concentrations. Reviews of micro-irrigation water quality describe mechanisms linking poor source quality with corrosion, scaling and clogging; experimental phosphate fertigation work finds that filter choice and operating pressure alter outcomes. Studies of reclaimed-water drip emitters offer examples of using discharge ratio and uniformity as maintenance indicators. These references justify robust acceptance tests, yet they should not be interpreted as providing universal Indonesian water-quality standards without site verification [49,53-55]. Theme 8 is the risk posed by fertiliser selection and concentration. Research on sediment-laden emitters has shown that certain phosphate formulations reduce sediment discharge from flow channels, while other fertiliser treatments behave differently. Further work on humic-acid compounds and newer organic fertiliser formulations documents possible interactions with fouling, but performance remains conditional on water chemistry. These studies do not imply that a particular additive is automatically an anti-clogging solution. They instead demonstrate that the fertiliser and the irrigation network must be designed together.

Procurement should specify water-soluble products of verified quality, injection calibration, backflow safeguards, staff training and demonstrable maintenance support under the actual plantation conditions [35,36,56,57]. Theme 9 concerns monitoring and automation. Sensors for soil water, line pressure, flow, electrical conductivity and pH can reveal deviations between commanded and delivered volumes. Data-driven irrigation research offers modelling options for estimating water need, but sophisticated algorithms cannot substitute for basic calibration or a valid physiological target. A low-cost manual system with disciplined checks might outperform an expensive, poorly maintained sensor platform, particularly where connectivity and technical staffing are intermittent.

The required level of automation should therefore increase only when its incremental value is demonstrated. Any computerised decision rule also needs override procedures for floods, equipment failures, prolonged rainfall, mixed fertiliser events and water-use restrictions [16,17,33]. Theme 10 concerns soil and field hydrology. Understorey vegetation and ground cover can improve infiltration in selected oil palm settings; Indonesian experiments have reported favourable infiltration responses for biomulch and different runoff behaviour in oil palm agroforestry. Catchment-scale research has also linked plantation soil compaction and evapotranspiration with discharge variation. These findings indicate that a fertigation installation should not replace soil conservation and rainwater management. In some environments, improving soil cover, reducing traffic compaction, managing terraces and targeting conventional nutrient placement may achieve greater returns per rupiah than constructing a water distribution network. Such alternatives belong in any fair feasibility comparison [27,58,59]. In Indonesia, a field investigation on former mining-land podzols found that bio-compost combined with reduced inorganic fertiliser inputs could improve soil quality and early oil palm productivity over a 12-month observation period.

Because that site and treatment differ from a mature commercial fertigation system, the study is best understood as evidence that lower-cost nutrient and soil management alternatives merit direct comparison, not as a transferable national yield estimate [60].

Independent Indonesian evidence also associates understorey vegetation with stronger soil-structure indicators, reinforcing its status as a serious alternative in lifecycle comparisons [39]. Theme 11 concerns climate variability beyond rainfall averages. Commercial Malaysian datasets have sometimes found much stronger variation among plantations than attributable to local monthly climatic anomalies, whereas Indonesian studies highlight substantial water-related and atmospheric drivers. These are not necessarily incompatible results: management heterogeneity, scale, temporal aggregation, cultivar composition and model specification may change the share of explained variation. A feasibility appraisal should therefore avoid single-climate-rule eligibility tests and instead estimate the avoided economic cost of identifiable dry-season stress at block level. Future climate projections may inform robustness testing, but they do not replace historical local hydrology, independent validation or evidence about access to water during drought events [2,14,24,52].

Recent regional analysis using 22 years of oil palm yield and climate observations across Indonesia and Malaysia has further shown that ENSO-related water stress is not spatially homogeneous. Atmospheric vapour pressure deficit and water-storage anomalies contributed differently across regions and ENSO phases. The appropriate inference for fertigation appraisal is therefore to estimate site-specific exposure and water availability, rather than to treat an El Niño signal as a uniform indicator of irrigation profitability [51]. Theme 12 addresses water accounting and rights. Water productivity can increase at palm level even when total catchment withdrawals rise, so an investment may improve farm ratios but worsen downstream seasonal supply. A recent Kampar catchment water-footprint study illustrates the relevance of separating green, blue and grey water components in Indonesian plantation settings. Irrigation design should consequently quantify incremental blue-water abstraction, storage losses, supply reliability, competing uses and potential changes to streamflow or groundwater. The environmental case is particularly weak when nominally efficient systems encourage expansion of irrigated area, rely on legally uncertain water abstraction or concentrate extraction during dry periods. Water allocation and environmental flow safeguards are prerequisites, not secondary project benefits [15,27,50]. Theme 13 is nitrogen and broader environmental performance. Studies outside oil palm indicate that drip fertigation can reduce some nitrogen loss pathways, but outcomes are highly dependent on how much N is applied and on the oxygen and moisture status of soil. Indonesian oil palm flux measurements demonstrate that nitrous oxide emissions can be substantial and variable at the ecosystem level, and Malaysian peat plantation measurements document fertiliser-associated N2O pulses.

Accordingly, the environmental evaluation must track soil mineral nitrogen, runoff or drainage when relevant, nutrient balance, energy requirements and emissions where feasible. Avoided runoff cannot be treated as demonstrated unless measured against an appropriately balanced conventional control [30,40-42]. A global water-saving irrigation meta-analysis reported lower overall global warming potential and higher water-use efficiency on average, yet also an increase in nitrous oxide emissions and a modest mean yield reduction. Its mixed outcomes reinforce the need to track separate greenhouse gases and farm performance, while avoiding direct transfer of pooled cross-crop effects to humid tropical oil palm [61]. Transport modelling under other fertigation systems indicates that the timing of nutrient delivery can alter nitrogen redistribution and the potential for nitrate leaching, making subsurface measurements valuable even when hydraulic uniformity appears acceptable [44].

Theme 14 is peatland suitability. Hydrological and carbon research shows that tropical peat landscapes are a fundamentally different investment context from mineral-soil plantations. Studies of rewetting oil palm peatland and of drainage-mediated photosynthetic response raise the importance of water tables and carbon losses, while modelling identifies temporal variability in peat emissions. Evidence from integrated water management in coconut peat cultivation illustrates the broader role of water control, though it is not an oil palm fertigation trial. A feasible decision process must screen out proposals that would intensify harmful drainage, degrade peat hydrology or conflict with restoration objectives.

For many peat settings, correct water-table management and peat protection are more relevant than fertiliser injection [45-48]. Theme 15 concerns the economics of additionality. The benefits often used in promotional discussions—improved yield, lower fertiliser losses, fewer application trips, or drought resilience—have different degrees of certainty and can overlap. Revenue from the same extra bunch must not be counted twice as both higher yield and higher productivity. A comprehensive model should separately track initial pumping and piping, storage and filtration, injector and control equipment, civil works, training, routine power and chemicals, maintenance labour, replacement parts and decommissioning. Investment may be reasonable for a compact, water-limited estate block with robust road access but unattractive for dispersed small holdings, even when the biological mechanism is sound. Uncertainty should be expressed as scenarios and break-even tests [8,10,18]. The comparative business case should begin with net cash flow under the best credible non-fertigation alternative. For example, if a package of nutrient audits, correctly formulated fertiliser and improved placement already increases yield, only the additional benefit from irrigation-assisted injection belongs in the fertigation case. A water-only intervention is also essential where drought is the binding constraint, since it reveals the difference between moisture relief and injection benefit.

Analyses of Indonesian independent smallholders reinforce that management deficiencies span multiple domains and that even modest agricultural improvements can raise profit. This substantially increases the evidentiary burden on costly systems before their incremental financial returns can be asserted [1,8,9]. Theme 16 concerns social and organisational readiness. Estates can integrate water management into centralised purchasing and monitoring, but they still require field staff who can diagnose nutrient deficiencies, operate chemical systems safely and enforce maintenance. Independent smallholders face smaller contiguous areas, difficult financing, unequal access to quality inputs and higher per-hectare transaction costs. Farmer diaries and interviews identify the cost of fertiliser and access to credit as major constraints, suggesting that infrastructure financing may be premature where routine nutrients remain unaffordable. Cluster-level installations could reduce certain fixed costs, but only if contractual rules for water allocation, billing, maintenance, liability and dispute resolution are credible. A technically functional network can fail economically through organisational breakdown [7,8,37]. Theme 17 concerns the potential for

precision nutrient management without full fertigation. Variable rates may be established using leaf and soil tests, zonal yield histories, field mapping and better fertiliser logistics, and these can be implemented with conventional equipment. Soil and palm nutrient requirements derived from yield relationships can provide a rational basis for rates. Fertigation adds value only where water movement, frequency and injection materially increase delivery performance at acceptable cost.

Studies on fertiliser formulations under drought also suggest that source chemistry affects agronomic outcomes independent of injection. The research therefore points to a staged technology ladder, not a binary choice between obsolete broadcasting and expensive automated fertigation [3,20,62]. Theme 18 is the quality of the existing evidence base. Mature oil palm plantations are long-lived, and trials differ in age, genotype, soil, surrounding climate and fertilisation history. Controlled irrigation-and-nutrition studies, smallholder observational analyses, hydrological measurements, and cross-crop fertigation syntheses all contribute valuable but non-interchangeable evidence. The local direct evidence still falls short of establishing a robust Indonesian national average incremental return from fertigation. Positive conclusions should therefore be framed as hypotheses conditional on trial evidence, with explicit descriptions of crop, location, intervention, comparator and measurement duration. Reporting uncertainty is a central finding rather than a defect to conceal in a single expected return figure [4,5,10,19].

Discussion and Analysis: Toward an Integrated Feasibility Decision

The synthesis answers the primary research question conditionally: fertigation may be technically and agronomically feasible in selected existing Indonesian oil palm blocks, but its financial and environmental feasibility is not currently established as a national generalisation. The strongest theoretical candidates combine meaningful seasonal root-zone water deficits, access to a reliable and legitimately allocated water supply, demonstrable nutrient management inefficiency and an implementable distribution layout. Even there, the choice must be validated relative to optimised conventional fertilisation and irrigation without nutrient injection. Where the dominant problem is severe K deficiency, weak harvesting discipline, inadequate cover management or poor planting materials, other improvements should be considered first. The goal is to remove the actual limiting factor at the lowest cost [3,7,19]. A practical site-screening process begins with the watershed and the soil, not with vendor specifications. Hydrological eligibility requires evidence of dry-period source water, legal abstraction, acceptable source chemistry, environmental flows and an assessed effect on neighbouring users. Agronomic eligibility requires sufficient palm stand health, realistic yield potential, active rooting zones, diagnosed nutrient need and evidence that supplementary irrigation can address a material deficit. Technical eligibility requires terrain-compatible network pressure, maintenance access, electrical reliability and chemical safety capacity. Investment eligibility then asks whether projected benefits over the life of the system remain positive under conservative prices, maintenance and yield-response assumptions. A failure at any earlier gate should stop or defer scale-up [15,49,50].

Hydraulic feasibility should also be demonstrated before the economic gate is passed, including field acceptance tests for distribution uniformity and water-source compatibility. Thus, Gate 3 in Figure 3 should be read as depending on technical serviceability, not simply an attractive spreadsheet estimate.

The best initial trial sites are not necessarily the driest sites. Extremely water-limited blocks may lack secure water reserves precisely when irrigation is needed, while sites with excessive rain or unreliable access to infrastructure may be unsuitable for a different reason. The target is a block with a material, addressable production constraint and sufficient implementation capacity. Soil type affects infiltration, drainage and the shape of the wetted volume; cultivar and palm age influence the time course of response. Selection should also account for block geometry, road infrastructure, sources of fuel or electricity, reservoir sediment loads, security of exposed piping and feasible positions for dosing and filtration equipment [13,23,31]. Field-scale sensor observations from Indonesian Ultisol and Spodosol plantations provide a practical precedent for testing how soil conditions and hardpan management change the moisture profile before a block is classified as irrigation-responsive [28]. Figure 3 converts the thematic evidence into an investment sequence in which legal and environmental eligibility is assessed before agronomic relevance, lifecycle economics and eventual scale-up. The framework is designed to prevent financial attractiveness from being used to override unacceptable hydrological impacts.

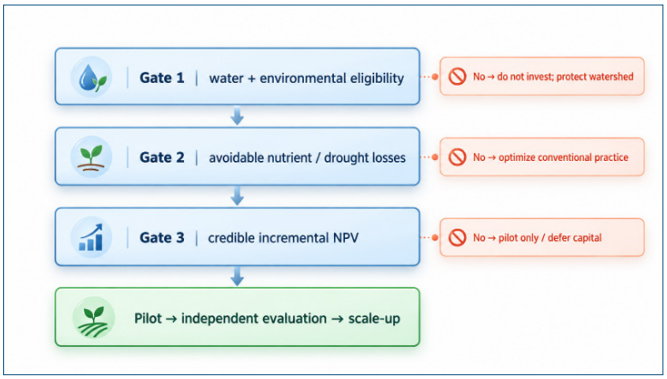


Figure 3: Sequential Decision Gates for Piloting and Scaling Fertigation (Original Decision Framework).

In Figure 3, a failed eligibility test triggers an alternative action rather than an automatic redesign of the fertigation proposal. Where the principal limitation is nutrient deficiency, improved conventional fertilisation is considered; where technical or economic uncertainties dominate, trial investment may proceed only at a controlled scale with independently evaluated outcomes. The decisive field experiment should use a replicated, preferably randomised-block arrangement across comparable age and soil strata. At minimum, treatments should include prevailing practice, optimised conventional nutrient management without new irrigation, optimised nutrient management with irrigation but separate fertiliser application, and full fertigation. If irrigation is locally irrelevant, an additional matched comparison between a proven optimal conventional regime and injected nutrients under equivalent water supply may be more efficient. Treatments must deliver comparable nutrient amounts when the aim is to measure placement and timing effects; a separate response surface can test whether total fertiliser dose can safely decline. Randomisation and pre-intervention baseline measurements guard against confusing intrinsic block fertility with treatment effects [4,11,21]. The comparative design should document any unavoidable differences in product solubility, nutrient formulation or injection frequency, because these factors can confound an estimate of delivery-method additionality. Where

funding permits, a supplementary treatment that holds dosing frequency constant can further distinguish the effects of timing from those of injection.

Outcome monitoring should cover both mechanism and final economic value. Record daily precipitation, water-table conditions where appropriate, soil matric potential or volumetric water content, actual irrigation delivery, emitter discharge uniformity, line pressure, fertiliser concentration, foliar nutrient concentration, fertiliser recovery indicators, monthly bunch production and bunch components. Financial records must disaggregate installation, energy, labour, fertiliser, maintenance, asset replacement and management time. Environmental measurements should include drainage or runoff quality where feasible, source abstraction and seasonal water availability, and targeted greenhouse gas measurements at representative sites. Where practical, maintain monitoring long enough to capture delayed reproductive yield responses and at least one major drought or wet-season contrast [17,22,26,40]. Attribution can be expressed as a set of incremental contrasts. The comparison between the optimised conventional treatment and the prevailing practice estimates the return to improved basic agronomy. The comparison between water-only irrigation and the optimised conventional treatment estimates the added value of water supply. The comparison between fertigation and water-only irrigation with matched nutrient rates estimates the incremental value of injecting fertiliser, including altered placement and frequency. A significant positive contrast in fruit yield is only the first condition; its monetised benefit must then exceed marginal infrastructure and operating costs.

This decomposition is especially important when a proposed demonstration bundles precision sensors, fertiliser source changes and better water management into a single package [1,4,9]. The recommended financial model is a discounted incremental cash-flow analysis. Let incremental cash flow in year t equal the value of additional marketable fresh fruit bunches, plus verifiable fertiliser and labour savings, minus additional energy, water, maintenance, labour, consumables and asset replacement. The project net present value is the initial capital outlay deducted from the discounted annual incremental cash flows, with a terminal salvage value added if justified. The discount rate must reflect financing and country-specific risk, while the evaluation horizon should be no longer than the credible service period without explicitly modelling renewal. A site is economically defensible only if net present value remains favourable under sufficiently conservative sensitivity cases, not merely at an optimistic central yield estimate [10,18]. Discount-rate and financing assumptions also require consistency: unlevered project cash flows should not deduct debt-service payments that are already reflected in the cost of capital. An equity-level appraisal may include financing cash flows, but must then use a corresponding equity discount rate.

$$NPV = -I_0 + \sum_{t=1}^{T} \frac{\Delta CF_t}{(1+r)^t} + \frac{SV_T}{(1+r)^T}$$

In this equation, I_0 denotes the initial capital investment, ΔCF_t denotes net incremental cash flow in year t (excluding any separately specified terminal value), r is the discount rate, T is the appraisal horizon, and SV_t denotes the justified terminal salvage value at year T. Annual cash flow and terminal value must be evaluated against the best credible alternative on a consistent after-cost basis. A useful break-even expression is the annualised incremental lifecycle cost per hectare divided by the realised net contribution margin per additional tonne of fruit. Its result is the required extra fresh fruit bunch production per hectare per year if there are no other monetisable savings. If independently verified savings exist, subtract these from annualised cost before computing the required yield. The expression makes commercial claims auditable: a vendor must specify how many extra tonnes are required and explain the physiological reason for expecting them. It also prevents a high gross yield figure from hiding low farmgate prices, costly pumping, poor equipment life or elevated repair costs. All parameters should be represented by ranges instead of invented Indonesian national averages [8,18].

$$\Delta Y_{BE} = max\{0, \frac{EAC - S}{M_{FFB}}\}$$

Here, ΔY_BE represents break-even additional fresh fruit bunch yield in tonnes per hectare per year, EAC is equivalent annual incremental lifecycle cost per hectare, S is verified annual non-yield savings per hectare, and M_FFB is the realised net contribution margin per additional tonne of fruit. The expression assumes a positive contribution margin and must be re-estimated whenever fertiliser use, energy cost, water availability or fruit prices change. All cash flows and annualised amounts must use the same price basis, time horizon and per-hectare allocation; savings included in S must not also be deducted from EAC. Sensitivity analysis should vary water demand and availability jointly rather than separately because the value of irrigation usually rises when supplies are most constrained. Other critical variables are baseline yield, fruit price, nutrient price and dose, expected marginal yield response, service life, pump energy use, repair frequency, cost of skilled operation, discount rate and asset utilisation across seasons. Monte Carlo analysis may be appropriate when decision-makers have credible probability distributions; otherwise, transparent low, central and high scenarios are preferable to pseudo-precision. In either case, environmental or legal noncompliance must not be treated as an acceptable low-probability outcome that can be offset by a large financial expected value [5,50].

The environmental comparison must distinguish field-level input efficiency from watershed sustainability. Minimising irrigation losses and improving nutrient targeting may lower some off-site externalities, but changes in total withdrawal, fertiliser rate and surface wetting can offset benefits. The review recommends monitoring irrigation blue-water use, nutrients lost per tonne of fresh fruit bunches, pump energy per hectare and per tonne, and any change in measured nitrogen emissions relative to the matched control. External climate-smart irrigation frameworks show why agronomic productivity and greenhouse gas performance should be optimised jointly. This reasoning is especially important in tropical conditions where heavy rain, alternating wetting and drying, or anaerobic patches can alter nutrient pathways [15,30,40]. Subsurface drip may reduce exposed hose disturbance and some evaporation pathways, but introduces diagnostic problems when lines are buried and plants have heterogeneous active roots. Surface drip allows inspection but increases exposure to field traffic, pests, plantation operations and theft. Micro-sprinkler approaches wet a different surface footprint and can impose different pressure, evaporation and maintenance trade-offs. It is premature to rank one architecture as best for all Indonesian estates without a location-specific hydraulic model and field trials. The technical decision should minimise cost per reliable kilogram of nutrient

delivered into a physiologically useful root zone, constrained by water availability and an acceptable maintenance risk threshold [16,33,54].

The economic evidence also suggests an equity issue. Infrastructure projects often lower per-unit fixed cost when concentrated over large blocks and tied to existing logistics, potentially advantaging corporate estates over independent growers. Cooperative infrastructure could reduce fixed costs but shifts the bottleneck toward collective governance, dispute resolution, cost-sharing and reliable payment. The first public-sector intervention should generally be access to diagnostics, balanced nutrients, extension and finance rather than untargeted subsidy of large fertigation equipment. Pilot support for farmer groups can be justified where shared water access and technical services are already organised and measurable incremental benefits can be demonstrated. Any support scheme should be evaluated against cheaper interventions competing for the same resources [1,7,8]. The peatland implication is unequivocally cautious. Given the hydrological and carbon importance of tropical peat, systems requiring drainage modifications or increased seasonal water manipulation should face a stricter environmental assessment than conventional mineral-soil pilots. The burden of proof includes peat-water management compatibility, subsidence risk, carbon dynamics and safeguards against fire and degradation. A technical ability to draw water from an existing canal cannot be read as permission or ecological justification to develop fertigation.

Research on peat rewetting and water-table responses suggests that restoring or preserving hydrological function may offer a more consequential sustainability intervention. Prioritising mineral-soil trials is consequently a reasonable precaution for early adoption studies [45-47]. An implementation roadmap can proceed in four phases. During diagnosis, estate managers map soils, characterise water sources, sample leaves, estimate crop water balance and benchmark current nutrient practice and costs. During pilot engineering, suppliers document source treatment, hydraulic design, injectors, safety controls and acceptance tests, with clear responsibility for operator training. During trial operation, independent agronomic and financial monitoring compares the specified counterfactual treatments and records all downtime and repairs. During scale-up, managers apply pre-agreed criteria for agronomic effect, lifecycle cash flow, environmental eligibility and organisational reliability. This sequence reduces the risk that enthusiasm for a novel delivery system displaces the evidence needed for an accountable capital investment [26,49,62].

The research agenda should concentrate on Indonesian mineral-soil contexts that reflect contrasting rainfall patterns and commercial structures. Longitudinal trials should include estates in dry-season-vulnerable regions and independent or grouped smallholders where water allocation is secure, with careful attention to nutrient balance and realistic baseline practices. Research institutions should also test soluble fertiliser chemistry in local raw-water conditions, compare the durability of exposed and buried systems, and evaluate the costs of maintaining uniform application under rain-driven sediment fluctuations. Published trial protocols should make control treatments, nutrient rates, doses, crop ages, soils, maintenance events and failure rates visible, allowing future syntheses to distinguish true transferability from apparent similarity [31,36,53]. Table 2 summarises the practical output of this qualitative synthesis as three different categories for management action, rather than a single unconditional technology recommendation. The categories establish a defensible sequence for site diagnosis and investment decisions, while leaving numerical thresholds to locally measured evidence.

Table 2: Conceptual Classification of Site-Specific Fertigation Feasibility.

Classification	Illustrative Conditions	Next Action
High-priority pilot	Secure dry-season water; mineral soil; diagnosed constraints; maintainable block	Run controlled, audited trial
Conditional	Agronomic value plausible but water, finance or reliability uncertain	Resolve bottlenecks; compare cheaper options
Do not prioritise	Water rights insecure; serious peat risk; weak need; inaccessible maintenance	Protect resources; use suitable alternatives

The site classes in Table 2 are proposed screening categories, not the results of a calibrated predictive model. Specific thresholds for crop response, water abstraction, acceptable emitter downtime and investment return should be set prospectively for each estate or farmer group. Several apparent contradictions become understandable within this decision framework. Crop meta-analyses can correctly identify mean benefits from drip fertigation while field-scale oil palm investment remains unproven because they evaluate different baselines and environmental settings. Substantial response to fertiliser can coexist with weak drought buffering because nutrient and water stress act at different stages of production. A system may simultaneously improve partial nutrient productivity and lose economic value if filtration and pumping costs dominate. Peatland drainage management may also be more important than irrigation efficiency. These are not arguments against further research; they are reasons to specify the causal comparison, site class and outcome metric precisely before any recommendation is generalised [5,18,19,47]. Finally, the feasibility matrix is intentionally hierarchical. Sites are classified as high-priority pilot candidates only when water access and environmental safeguards are satisfied and when agronomic need, technical serviceability and a credible incremental business case align. Conditional sites require remedial diagnosis, a lower-cost management programme or a narrow experimental trial before infrastructure expansion. Unsuitable sites fail a fundamental water, ecological or organisational gate even if a commercial supplier predicts higher yield. This approach makes evaluation transparent to agronomists, engineers, financial managers and community stakeholders, while explicitly preserving the ability to reject a technically impressive but poorly justified investment.

Conclusions and Recommendations

Fertigation should be regarded as a conditional intensification option for existing Indonesian oil palm plantations, not a universally applicable technology package. The literature offers persuasive reasons to improve water and nutrient synchronisation, and strong direct evidence that poor nutrient management

and water stress constrain oil palm production. It does not yet establish a reliable Indonesia-wide estimate of the incremental yield, profitability or environmental benefit of nutrient injection compared with optimised conventional fertilisation and irrigation without injection. Technical possibility and investment feasibility must therefore be treated as separate conclusions. The agronomic recommendation is to begin with diagnosis. Leaf nutrient status, realistic yield potential, fertiliser balance, seasonal soil water shortage and root-zone characteristics should determine whether an additional distribution system addresses a meaningful limitation. The engineering recommendation is to test water quality and fertiliser compatibility, design reliable filtration and pressure controls, establish flushing and calibration procedures, and fully budget the effort needed for safe operation. In many plantations, improved conventional fertiliser rates, placement and timing alongside soil conservation may be the more credible first investment.

The financial recommendation is to require incremental net present value and a clear break-even yield response relative to the best realistic alternative. Optimistic yield assumptions from non-oil-palm fertigation literature should never be used as unadjusted project forecasts. A transparent pilot should include equivalent-nutrient water-only and conventional controls, capture delayed palm yield responses, and record lifecycle equipment, electricity, labour and maintenance costs. A project should not proceed to scale merely because a demonstration records more bunches in a poorly fertilised control. The environmental recommendation is to protect water access, downstream users and sensitive soils as binding conditions. Changes in blue-water abstraction, nutrient losses, energy use and nitrous oxide emissions should be monitored where relevant. Peatland holdings should be subject to particularly cautious assessment because broader water-table and carbon management objectives may outweigh any potential delivery advantage. Adoption arrangements should also be designed around the capacity of the responsible operator, rather than assuming that centralised estate infrastructure can be reproduced at smallholder scale without financing and governance support. Future research should prioritise long-duration Indonesian comparative trials, multi-season hydraulic reliability measurements, site-specific financial evaluations and transparent environmental accounting. Policymakers and research institutions can help by supporting open trial protocols, technical training, realistic credit products and extension for balanced nutrient management before subsidising equipment. The substantive conclusion is that fertigation can be worth investigating where water limitations and nutrient delivery inefficiencies coincide, but scaling should follow documented additionality, economic robustness and environmental eligibility rather than a generalised promise of precision agriculture.

References

1. Monzon, J.P., Lim, Y.L., Tenorio, F.A., Farrasati, R., Pradiko, I., et al. (2023). Agronomy explains large yield gaps in smallholder oil palm fields. Agricultural Systems, 210, 103689.
2. Monzon, J.P., Jabloun, M., Cock, J., Caliman, J.P., Couëdel, A., et al. (2022). Influence of weather and endogenous cycles on spatiotemporal yield variation in oil palm. Agricultural and Forest Meteorology, 314, 108789.
3. Sugianto, H., Monzon, J.P., Pradiko, I., Tenorio, F.A., Lim, Y.L., et al. (2023). First things first: Widespread nutrient deficiencies limit yields in smallholder oil palm fields. Agricultural Systems, 210, 103709.
4. Arifin, I., Hanafi, M.M., Roslan, I., Ubaydah, M.U., Karim, Y.A., et al. (2022). Responses of irrigated oil palm to nitrogen, phosphorus and potassium fertilizers on clayey soil. Agricultural Water Management, 274, 107922.
5. Delbaz, R., Ebrahimian, H., Abbasi, F., Ghameshlou, A.N., Liaghat, A.M., et al. (2023). A global meta-analysis on surface and drip fertigation for annual crops under different fertilization levels. Agricultural Water Management, 289, 108504.
6. Xiao, Y., Puig-Bargués, J., Zhou, B., Li, Q., Li, Y. (2020). Increasing phosphorus availability by reducing clogging in drip fertigation systems. Journal of Cleaner Production, 262, 121319.
7. Lim, Y.L., Tenorio, F.A., Monzon, J.P., Sugianto, H., Donough, C.R., et al. (2023). Too little, too imbalanced: Nutrient supply in smallholder oil palm fields in Indonesia. Agricultural Systems, 210, 103729.
8. de Vos, R.E., Lim, Y.L., Donough, C.R., Monzon, J.P., Tenorio, F.A., et al. (2026). Fertilizer use in Indonesian oil palm smallholder systems: agronomic and socio-economic constraints and opportunistes. Environment, Development and Sustainability, 1-20.
9. Sugianto, H., Donough, C.R., Monzon, J.P., Pradiko, I., Lim, Y.L., et al. (2025). Improving yield and profit in smallholder oil palm fields through better agronomy. Agricultural Systems, 224, 104269.
10. Bandyopadhyay, A., Ghosh, D.K., Biswas, B., Parameswarappa, M.H., Timsina, J. (2020). Fertigation effects on nutrient use efficiency, energy productivity, and economics of coconut (cocos nucifera L.) cultivation in the eastern indo-gangetic Plains of South Asia. International journal of fruit science, 20(sup3), S1483-S1494.
11. Wang, H., Wu, L., Wang, X., Zhang, S., Cheng, M., et al. (2021). Optimization of water and fertilizer management improves yield, water, nitrogen, phosphorus and potassium uptake and use efficiency of cotton under drip fertigation. Agricultural Water Management, 245, 106662.
12. Yang, X., Zhang, L., Liu, X. (2024). Optimizing water-fertilizer integration with drip irrigation management to improve crop yield, water, and nitrogen use efficiency: A meta-analysis study. Scientia Horticulturae, 338, 113653.
13. Sukarman, S., Saidy, A.R., Rusmayadi, G., Adriani, D.E., Primananda, S., et al. (2022). Effect of water deficit of Ultisols, Entisols, Spodosols, and Histosols on oil palm productivity in Central Kalimantan. SAINS TANAH-Journal of Soil Science and Agroclimatology, 19(2), 180-191.
14. Afandi, A.M., Zulkifli, H., Nur Zuhaili, H.A.Z.A., Norliyana, Z.Z., Hisham, H., et al. (2023). Oil palm water requirement and the need for irrigation in dry Malaysian areas. Journal of Oil Palm Research, 35(3), 391-405.
15. Anand, S.K., Rosa, L., Mohanty, B.P., Rajan, N., Calabrese, S. (2025). Balancing productivity and climate impact: A framework to assess climate-smart irrigation. Earth's Future, 13(11), e2025EF006116.
16. Bounajra, A., El Guemmat, K., Mansouri, K., Akef, F. (2024). Towards efficient irrigation management at field scale using new technologies: A systematic literature review. Agricultural Water Management, 295, 108758.
17. Togneri, R., Prati, R., Nagano, H., Kamienski, C. (2023). Data-driven water need estimation for IoT-based smart

irrigation: A survey. Expert Systems with Applications, 225, 120194.
18. Fu, H., Huang, Y., Chen, L., Wang, X., Li, T., et al. (2026). Drip fertigation: A potential triple-win strategy for improving crop yields, reducing water use, and enhancing eco-economic benefits. European Journal of Agronomy, 178, 128149.
19. Wandri, R., Monzon, J.P., Carciochi, W.D., Hairiah, K., Suprayogo, D., et al. (2025). Can improved plant nutrition buffer against water-related yield losses in oil palm. Agricultural Water Management, 322, 109980.
20. Farrasati, R., Carciochi, W., Lim, Y.L., Donough, C.R., Monzon, J.P., et al. (2026). Quantifying plant nutrient requirements in oil palm. European Journal of Agronomy, 176, 128054.
21. Chtouki, M., Naciri, R., Garré, S., Nguyen, F., Zeroual, Y., et al. (2022). Phosphorus fertilizer form and application frequency affect soil P availability, chickpea yield, and P use efficiency under drip fertigation. Journal of Plant Nutrition and Soil Science, 185(5), 603-611.
22. Hermanto, A., Gan, S.H., Mustopa, I.R., Wong, W.C., Ng, P.H.C., et al. (2023). Use of multiseasonal oil palm yield data to assess drought tolerance. Scientia Horticulturae, 308, 111603.
23. Bayona-Rodríguez, C., Romero, H.M. (2024). Drought resilience in oil palm cultivars: A multidimensional analysis of diagnostic variables. Plants, 13(12), 1598.
24. Pradiko, I., Hariyadi, H., June, T. (2023). Quantification of Climate Factors Contributing to Variation of Oil Palm Yield. Jurnal Penelitian Kelapa Sawit, 31(2), 108-123.
25. Idris, S., Sung, C.T.B., Zaibon, S., Cheak, S.C. (2026). Climate variability and water Stress effects on oil palm (Elaeis guineensis Jacq.) productivity in Malaysia. Journal of Oil Palm Research, 38(1), 1-34.
26. Pradiko, I., Rahutomo, S., Farrasati, R., Ginting, E.N., Hidayat, F., et al. (2023). Transpiration of oil palm (Elaeis guineensis Jacq.) based on sap flow measurement: the relation to soil and climate variables. Journal of Oil Palm Research, 35(1), 168-184.
27. Tarigan, S., Stiegler, C., Wiegand, K., Knohl, A., Murtilaksono, K. (2020). Relative contribution of evapotranspiration and soil compaction to the fluctuation of catchment discharge: case study from a plantation landscape. Hydrological Sciences Journal, 65(7), 1239-1248.
28. Sukarman, S., Sutiarso, L., Suwardi, S., Wirianata, H., Nugroho, A.P., et al. (2024). Analysis of water behavior in oil palm plantations on Spodosol and Ultisol using soil moisture content monitoring system (SMCMS). Jurnal Penelitian Kelapa Sawit, 32(1), 1-22.
29. Delbaz, R., Ebrahimian, H., Abbasi, F., Ghameshlou, A.N., Liaghat, A., et al. (2023). A global meta-analysis on surface and drip fertigation for annual crops under different fertilization levels. Agricultural Water Management, 289, 108504.
30. Zheng, J., Zhou, M., Zhu, B., Fan, J., Lin, H., et al. (2023). Drip fertigation sustains crop productivity while mitigating reactive nitrogen losses in Chinese agricultural systems: Evidence from a meta-analysis. Science of the Total Environment, 886, 163804.
31. Shen, Y., Puig-Bargués, J., Li, M., Xiao, Y., Li, Q., et al. (2022). Physical, chemical and biological emitter clogging behaviors in drip irrigation systems using high-sediment loaded water. Agricultural Water Management, 270, 107738.
32. Wang, Y., Puig-Bargués, J., Ma, C., Xiao, Y., Maitusong, M., et al. (2024). Influence and selection of nitrogen and phosphorus compound fertilizers on emitter clogging using brackish water in drip irrigation systems. Agricultural Water Management, 291, 108644.
33. Zaiyu, L., Yan, M., Hao, G., Shihong, G., Yanqun, Z., et al. (2025). The hydraulic performance and clogging characteristics of a subsurface drip irrigation system operating for five years in the North China plain. Agricultural Water Management, 307, 109217.
34. Chtouki, M., Naciri, R., Oukarroum, A. (2024). A review on phosphorus drip fertigation in the Mediterranean region: Fundamentals, current situation, challenges, and perspectives. Heliyon, 10(3).
35. Wang, Y., Muhammad, T., Liu, Z., Ma, C., Zhang, C., et al. (2022). Compounding with humic acid improved nutrient uniformity in drip fertigation system using brackish water: The perspective of emitter clogging. Agricultural Water Management, 269, 107670.
36. Hou, P., Liu, L., Tahir, M., Li, Y., Wang, X., et al. (2024). Effect of fertilization on emitter clogging in drip irrigation using high sediment water: Perspective of sediment discharge capacity. Agricultural Water Management, 294, 108723.
37. de Vos, R.E., Nurfalah, L., Tenorio, F.A., Lim, Y.L., Monzon, J.P., et al. (2023). Shortening harvest interval, reaping benefits? A study on harvest practices in oil palm smallholder farming systems in Indonesia. Agricultural Systems, 211, 103753.
38. 38. Huang Chai Khoo, B., Chang, Y.Y., Sim, C.C., Abd Wahid, S.A., Nazli, M.H., et al. (2026). Controlled release fertiliser as an alternative nutrient management strategy for immature oil palm establishment on steep terrain: growth and foliar nutrient responses. Frontiers in Plant Science, 17, 1846207.
39. Thoumazeau, A., Mettauer, R., Junedi, H., Baron, V., Chéron-Bessou, C., et al. (2024). Effects of fertilization practices and understory on soil health and oil palm performances in smallholdings: An Indonesian case study. Agricultural Systems, 213, 103802.
40. Stiegler, C., Koebsch, F., Ali, A.A., June, T., Veldkamp, E., et al. (2023). Temporal variation in nitrous oxide (N2O) fluxes from an oil palm plantation in Indonesia: An ecosystem-scale analysis. GCB Bioenergy, 15(10), 1221-1239.
41. Wei, Q., Xu, J., Liu, Y., Wang, D., Chen, S., et al. (2024). Nitrogen losses from soil as affected by water and fertilizer management under drip irrigation: Development, hotspots and future perspectives. Agricultural Water Management, 296, 108791.
42. Zawawi, N.Z., Khoon, K., Murdi, A.A., Arn, T. (2024). Quantifying the effect of fertiliser application on nitrous oxide pulses in oil palm plantation. Journal of Oil Palm Research, https://jopr.mpob.gov.my/files/2024/05/joprv37dec2025-norliyana.pdf.
43. Zhang, L., Zhao, Z., Wu, X., Yang, Y., Wang, H., et al. (2025). Drip irrigation in dryland agriculture controls soil water-filled pore space and reduces greenhouse gas emissions: A meta-analysis. Water Resources Research, 61(9), e2024WR039388.
44. Chen, R., Chen, X., Li, H., Wang, J., Guo, X. (2025). Evaluating soil water and nitrogen transport, nitrate leaching

and soil nitrogen concentration uniformity under sprinkler irrigation and fertigation using numerical simulation. Journal of Hydrology, 647, 132345.
45. Novita, N., Asyhari, A., Ritonga, R.P., Gangga, A., Anshari, G.Z., et al. (2024). Strong climate mitigation potential of rewetting oil palm plantations on tropical peatlands. Science of the total environment, 952, 175829.
46. McCalmont, J., Kho, L.K., Teh, Y.A., Chocholek, M., Rumpang, E., et al. (2023). Oil palm (Elaeis guineensis) plantation on tropical peatland in South East Asia: Photosynthetic response to soil drainage level for mitigation of soil carbon emissions. Science of the Total Environment, 858, 159356.
47. Swails, E., Hergoualc'h, K., Deng, J., Frolking, S., Novita, N. (2022). How can process-based modeling improve peat CO2 and N2O emission factors for oil palm plantations?. Science of the total environment, 839, 156153.
48. Fawzi, N.I., Sumawinata, B., Rahmasary, A.N., Qurani, I.Z., Naufaldary, R.G., et al. (2024). Integrated water management practice in tropical peatland agriculture has low carbon emissions and subsidence rates. Heliyon, 10(5).
49. Anyango, G.W., Bhowmick, G.D., Bhattacharya, N.S. (2024). A critical review of irrigation water quality index and water quality management practices in micro-irrigation for efficient policy making. Desalination and Water Treatment, 318, 100304.
50. Titisari, P.W., Chahyana, I., Permatasari, T., Elfis. (2026). The water footprint of oil palm plantation in the Kampar catchment, Riau, Indonesia. Journal of Oil Palm Research, https://jopr.mpob.gov.my/wp-content/uploads/2026/01/joprinpress2026-prima.pdf
51. Naito, C., Takeuchi, W. (2026). Regional water stress dynamics in oil palm under ENSO in Malaysia and Indonesia using 22-year multiple climate data. Scientific Reports, https://www.nature.com/articles/s41598-026-63806-3.
52. Fleiss, S., McClean, C.J., King, H., Hill, J.K. (2022). Limited impacts of climatic conditions on commercial oil palm yields in Malaysian plantations. CABI Agriculture and Bioscience, 3(1), 59, https://doi.org/10.1186/s43170-022-00127-1.
53. Liu, C., Wang, R., Wang, W., Hu, X., Wu, W., et al. (2022). Different irrigation pressure and filter on emitter clogging in drip phosphate fertigation systems. Water, 14(6), 853.
54. Liu, X., Zhang, L., He, X. (2022b). Emitter clogging characteristics under reclaimed wastewater drip irrigation: A meta-analysis. Journal of the Science of Food and Agriculture, 102(10), 4171-4181.
55. Wang, H., Hu, X., Wang, W., Ma, X. (2025). Main influence indicators and regulatory pathways of emitter clogging under physical and chemical combination factors. Agricultural Water Management, 310, 109383.
56. Liu, Z., Xu, L., Bai, Y., Wang, Y., Tian, L., et al. (2026). Mitigating emitter clogging in high-sediment water drip irrigation systems through selection of appropriate organic fertilizers. Agricultural Water Management, 332, 110482.
57. Zhang, Z., Ai, P., Zhang, C., Liu, W., Zang, W., et al. (2026). Coupled Effects of Fertilizer and Sediment on Drip Irrigation Emitter Clogging and Its Implications for Sustainable Water–Fertilizer Management. Sustainability, 18(10), 4663.
58. Khalida, R., Guntoro, D. (2021). Pemanfaatan Asystasia gangetica (L.) T. Anderson sebagai Biomulsa untuk Meningkatkan Laju Infiltrasi pada Lahan Kelapa Sawit Menghasilkan. Jurnal Agronomi Indonesia (Indonesian Journal of Agronomy), 49(3), 316-322.
59. Ullyta, A., Tarigan, S.D., Wahjunie, E.D. (2022). Infiltrasi dan Aliran Permukaan pada Agroforestri dan Kelapa Sawit. Indonesian Journal of Agricultural Sciences/Jurnal Ilmu Pertanian Indonesia, 27(3), 359.
60. Supriatna, J., Setiawati, M.R., Sudirja, R., Suherman, C. (2026). Enhancing soil fertility, inorganic fertilizer efficiency, and oil palm productivity through bio-compost application in oxium biodegradable sacks on former mining land-podzols: Insights from a field study in Indonesia. Journal of the Saudi Society of Agricultural Sciences, 25(1), 1.
61. Tan, M., Cui, N., Jiang, S., Xing, L., Wen, S., et al. (2025). Effect of practicing water-saving irrigation on greenhouse gas emissions and crop productivity: A global meta-analysis. Agricultural Water Management, 308, 109300.
62. Fang Wen, N., Jing Jie, L. (2025). Agronomic and Economic Efficacy of Nitrate-Based Compound Fertilizer in Replacing Straight Fertilizers Application on Oil Palms Planted in Semiarid Regions. International Journal of Agronomy, 2025(1), 3551465.

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