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Prerequisites for effective fertigation in Indonesian oil palm plantations: a review of biophysical readiness, engineering reliability and institutional capacity

Abstract

Fertigation is increasingly proposed as an integrated means of supplying water and dissolved nutrients to oil palm, yet implementing the technology is not equivalent to demonstrating its value. This qualitative literature review identifies conditions that must be established before commercial adoption in Indonesia. It interprets journal studies published from January 2020 to October 2026, prioritising Indonesian mature oil palm evidence and treating findings from other palms and annual crops as conditional analogies. The ten sequential prerequisites are (1) verified water limitation; (2) scientifically established nutrient requirements; (3) legitimate and dependable water supply; (4) suitable source-water chemistry and soluble fertilisers; (5) field-verified hydraulic uniformity; (6) reliable energy, maintenance and operator competence; (7) meaningful information and monitoring; (8) an optimised baseline and credible causal comparison; (9) risk-adjusted incremental financial performance; and (10) ecological safeguards and institutional legitimacy. These ten correspond directly to Sections 4.1–4.10 and form four interacting domains. Existing research documents heterogeneous water stress, nutrient imbalances, management constraints and emitter-clogging risks but does not establish a transferable national yield premium for fertigation in mature Indonesian oil palm. A phase-gate pathway compares adoption against optimised conventional management and permits redesign, deferral or rejection. Multi-site, multi-season comparative trials are required before broad scale-up.

Keywords: oil palm; fertigation; prerequisites; Indonesia; plantation irrigation; nutrient management; water governance; hydraulic reliability; technology readiness; economic feasibility

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Introduction

Background and problem definition

A successful fertigation installation is not necessarily an effective agronomic intervention. Equipment can distribute water and fertiliser according to specifications while failing to relieve the constraint that actually limits fresh fruit bunch production. In humid tropical plantations, supplementary water may be unnecessary in many months; low production may instead reflect inadequate nutrient balance, planting material, drainage, harvesting intervals or field access. Indonesia therefore needs a prerequisite-oriented assessment: which conditions should be verified before a manager or farmer group commits capital to pumps, injection units and pipe networks? The distinction matters because Indonesia's yield gaps are demonstrably related to conventional agronomic practices and management heterogeneity, neither of which can be corrected automatically by a delivery technology.[1–4]

Fertigation refers to the controlled injection of soluble nutrient products into an irrigation flow, with delivery timing, dose and position coordinated with crop demand. The practice can offer advantages where crops face recurring water deficits, and nutrients move inefficiently through the soil, but the same logic becomes fragile where annual rainfall meets demand, the water source is unreliable, or the relevant fertiliser cannot be supplied economically in soluble form. Imported evidence from short-cycle crops is useful for engineering design yet cannot be treated as a mature oil-palm yield estimate. This article treats prerequisites as testable conditions for performance rather than a list of attractive technologies to purchase (Li et al., 2021).[5–7]

Why Indonesian oil palm is a difficult application

Indonesia's oil-palm environments differ in effective rainfall, dry-spell length, soil texture, hardpan formation, slope, water-table dynamics, access roads and ownership structure. A water deficit measured on one soil may produce a different productive response on another, and a climatic anomaly may affect bunch formation long before its effect reaches harvest records. Thus, mean annual rainfall is insufficient for specifying a fertigation requirement. The threshold for considering irrigation must depend on the time and depth of water limitation, biological response lags and practical alternatives such as ground cover, soil rehabilitation, mulching or improved drainage.[8–12]

The industry also combines technically staffed estates with independent smallholders who may face acute fertiliser affordability and procurement problems. In such settings, a capital-intensive solution may increase inequality unless shared-service, maintenance and water-allocation arrangements are demonstrably workable. Fertigation depends on continuous operation rather than a single fertiliser purchase: spare parts, compatible products, energy, calibration and timely repairs are integral to its value. The prerequisite lens therefore has a social dimension; commercial feasibility depends on who controls water, bears failure risk and finances the useful life of the system.[13–16]

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Research gap, aim and contribution

The evidence base for oil-palm nutrient response, yield variation, soil moisture and plantation hydrology has expanded, as has research on drip-injection performance in other crops. Yet these literatures are often interpreted separately: agronomists diagnose yield constraints, engineers optimise distribution uniformity, economists examine capital costs, and social scientists assess adoption barriers. Missing is a coherent test of how these conditions must fit together for fertigation to be useful. The present review builds an integrated prerequisite architecture and explicitly distinguishes prerequisite fulfilment from eventual proof of agronomic effectiveness.[17–20]

The article asks not whether fertigation is inherently modern or sustainable, but when its implementation can be justified by evidence. Its objectives are to identify the sequential and jointly necessary prerequisites, clarify feasible measurements and decision thresholds, distinguish plantation contexts requiring separate treatment, and propose a responsible pathway from diagnosis to multi-season validation and investment. This contributes a decision-oriented analytical framework rather than a quantitative national forecast. It leaves room for non-adoption when existing management can remedy the principal constraint at lower private and social cost.[21–24]

Literature review

Integrated input management versus technology adoption

Fertigation is a coupling mechanism: irrigation manages root-zone water status while fertiliser injection determines the timing and spatial delivery of dissolved nutrients. Potential efficiency arises only if water timing is physiologically relevant and the injected nutrient is both needed and accessible to active roots. This conditional relationship is more demanding in a perennial palm than in an annual vegetable crop because nutrient demands, reproductive processes and root activity vary across time and space. A prerequisite-based perspective resists equating narrower fertiliser bands, automatic valves or higher distribution uniformity with sustainable increases in harvested yield.[25–28]

Biophysical necessity and crop-response theory

A central agronomic prerequisite is a demonstrated limiting factor: an actual difference between water or nutrient supplied and the amount needed for attainable growth. Water deficits should be characterised at daily or weekly resolution using rainfall, atmospheric demand, soil water storage and, where appropriate, shallow groundwater. Production responses must then be interpreted over the long oil-palm reproductive cycle. Studies of Indonesian soils and climate show that water limitation is heterogeneous and lagged; therefore, a direct translation from an irrigation schedule designed for other crops is scientifically weak.[29]

Plant nutrition represents a related but distinct prerequisite. A site can be water-limited, nutrient-limited, both, or neither, and each state implies a different intervention. Fertiliser-use efficiency is also multidimensional: yield per unit applied, incremental yield response, recovery of applied nutrients and changes in soil reserves are not interchangeable. Fertigation requires a complete nutrient budget, including harvested export and reserves, rather than simply replacing granular products with more costly soluble materials. Research on potassium and magnesium utilisation in Sumatra and emerging nutrient-requirement estimates underline the need for site-specific fertilisation rather than generic soluble recipes.[30,31]

Engineering reliability and operational resilience

Engineering studies define a second theoretical boundary: a system's design performance differs from its field service performance. Sediment, mineral precipitation, biological growth and root intrusion can reduce discharge or change nutrient concentration along a lateral. The chemistry of the water-fertiliser mixture, hydraulic pressure and operator response must therefore be assessed as a system. Pressure-compensating components do not eliminate the need for filtration, field measurement, maintenance logs or periodic recalibration. An equipment vendor's catalogue cannot establish reliability under local Indonesian source-water conditions.[32–35]

Technology readiness additionally depends on energy continuity and the ability to notice failures. Solar pumping, remote sensors and automatic scheduling may lower some recurrent costs, but they add batteries, electronics, telecommunications and software to the maintenance chain. A technically elegant design that cannot be repaired during a drought is not operationally ready. Useful automation should build on verified irrigation uniformity, a conservative fail-safe state and the ability to suspend injection when pressure or flow is abnormal. These principles have support in cross-crop irrigation and energy systems, although quantitative savings are site-specific.[36–40]

Institutional fit and environmental externalities

Investment theory provides the economic threshold: only the incremental value over the best feasible comparator is attributable to fertigation. Upfront pumps, piping and source works must be assessed alongside water treatment, compatible fertiliser price premiums, replacement schedules, labour, energy and delayed bunch response. A project may improve a water-use efficiency ratio while still having negative incremental net present value. Its social evaluation must consider who owns shared infrastructure, allocates scarce water and assumes debt after the pilot ends. The most suitable management option can be optimised broadcast fertiliser, a hybrid approach or improved soil-water conservation rather than hydraulic equipment.

Finally, plot-scale resource savings do not automatically imply acceptable watershed outcomes. Added irrigation can increase blue-water withdrawals even when water productivity improves, and nutrient losses depend on fertiliser mass, application timing and drainage pathways. Peat soils add carbon, subsidence, fire and water-table considerations that may dominate the fertigation question. An adequate prerequisite concept must therefore include ecological exclusion and social safeguards at the beginning, not merely environmental monitoring after systems are installed.[41–44]

Methodology: qualitative literature review

Interpretive design and scope

This study uses a qualitative literature review (QLR), not a systematic literature review or a newly conducted meta-analysis. Its purpose is to interpret and connect agronomic, hydrological, engineering, financial, environmental and institutional evidence, especially when direct field experiments in Indonesian mature oil palm are scarce. Peer-reviewed studies dated January 2020 through 23 October 2026 form the stated evidentiary window. The closing date is a bibliographic eligibility cut-off recorded in the source manuscript, not a verified date of the last database search. The analysis neither reports a PRISMA process nor claims exhaustive capture of all studies; the contribution is an explicit, critically reasoned integration of context-dependent prerequisites.

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Source selection and evidence hierarchy

Studies were prioritised through purposive exploration of journal literature addressing oil-palm water constraints, nutrient uptake, fertigation, drip hydraulics, environmental effects, renewable-powered pumping and technology adoption. The strongest inference tier comprises investigations of Indonesian oil-palm plantations and farmers. A second tier comprises international mature oil-palm research, while a third includes coconut and annual-crop fertigation experiments, laboratory hydraulics and global irrigation syntheses. Cross-crop evidence is used to identify plausible mechanisms, equipment risks and research design, not to assign a transferable oil-palm yield premium.[45,46]

To make source discovery inspectable, a retrospective search specification was reconstructed from the retained literature. The three query families are: (A) ("oil palm" OR "Elaeis guineensis") AND ("fertigation" OR "drip irrigation" OR "soil moisture" OR "water deficit" OR "nutrient uptake"); (B) ("fertigation" OR "drip irrigation") AND ("emitter clogging" OR "hydraulic uniformity" OR "water chemistry" OR "fertiliser compatibility"); and (C) ("oil palm" OR "Elaeis guineensis") AND ("water footprint" OR "water rights" OR "smallholder" OR "economic feasibility" OR "peatland"). Operators and field tags require adaptation to each bibliographic interface.

These strings can be rerun in Scopus, Web of Science, Google Scholar or Crossref for an independent follow-up review, followed by publisher-website verification of bibliographic records and full texts. These are specified as replicable retrieval routes; the original platform-by-platform search log has not been preserved, so the review does not claim that each named database was consulted during initial manuscript preparation. In the present revision the publisher record for Titisari et al.[41] was checked directly. This distinction prevents a retrospective reconstruction from being misrepresented as a prospectively logged search.

For retrospective assessment of the retained synthesis, an explicit eligibility rule is now stated: relevance to at least one prerequisite and publication in a peer-reviewed journal during the defined 2020–2026 window. Indonesian mature oil palm research was prioritised, followed by international mature palm studies and explicitly identified mechanism-based analogies from other crops or laboratory irrigation systems. Non-peer-reviewed marketing material, unsupported yield-premium assertions, untraceable records, and research outside the evidence window are not treated as admissible empirical support. No defensible English-only restriction can be inferred from the original review: English- and Indonesian-language research could qualify when the source and methods could be evaluated.

An audit of the manuscript identifies 64 distinct journal references; 60 are cited directly in the prerequisite synthesis in Section 4, and four provide other background or interpretive support elsewhere in the article. No original hit count, abstract-screening count, exclusion log or division of initially screened records survives in the provided material. Such counts are therefore not reconstructed or presented as PRISMA-style outputs. These limits are a material restriction on the search reproducibility of the current qualitative review.

Coding, comparison and reflexivity

An initial analytic codebook covered hydroclimatic need, palm nutrition, water rights, source-water quality, solution compatibility, hydraulic distribution, energy and maintenance, sensors, financing, environmental impacts, institutional capacity and validation design. Articles were compared for context, unit of analysis, intervention type, comparator quality, measurement period and strength of inference. Deductive themes were revised where evidence showed interacting conditions, such as strong nutritional responses that did not eliminate losses caused by water stress. The synthesis is intentionally explicit about uncertainty and avoids turning observational relationships or crop-specific meta-analyses into causal claims for Indonesian oil palm.[47]

Limits of inference

Publication and site-selection bias may favour technologically successful pilots, while trials lasting one crop season cannot capture the full delay between water stress and oil-palm harvest. Laboratory emitter tests illuminate failure modes without measuring plantation-scale reliability. Moreover, many Indonesian smallholder studies describe constraints on conventional fertiliser practice rather than direct fertigation adoption. No original field measurements, water permits, bills of quantities, cost quotations or farmer interviews were generated for this paper, and the numerical decision expressions below are diagnostic formulae rather than estimated outcomes.

Results: thematic prerequisites

Prerequisite 1: a verified water limitation

The first prerequisite is evidence that supplementary water can correct a recurrent and agronomically meaningful deficit. Site qualification requires a multi-year record of daily rainfall, reference atmospheric demand, root-zone storage and crop water status, supplemented by soil moisture observations in representative blocks. Seasonal and spatial information is essential because a high annual rainfall total can coexist with harmful dry periods, whereas another site may be wet enough that most installed irrigation capacity stays idle. The relevant proof is an identified shortage at the palm's active uptake zone, not simply a regional classification as drought-prone; simulation and Malaysian climate studies are supporting analogies rather than Indonesian field-effect estimates.[25,29]

The same rainfall anomaly cannot define an equal irrigation prescription across soils. In Central Kalimantan, differences among Ultisols, Entisols, Spodosols and Histosols were associated with different sensitivities of bunch productivity to water deficits; delayed harvest effects reinforce the need to avoid interpreting a single dry season as a complete treatment response.[48] Soil hydraulic testing should therefore consider texture, infiltration, compaction, rooting restrictions and drainage before irrigation is proposed. Where frond placement, cover crops and infiltration management adequately buffer short deficits, they form part of the economically relevant comparison.

Prerequisite 2: a scientifically established nutrient requirement

A second prerequisite is an evidence-based nutrient budget for the target palm age, yield potential, soil reserves and planned bunch removal. Leaf analysis, calibrated soil sampling, field history and input records should determine whether nitrogen, potassium, magnesium, phosphorus or other elements genuinely limit performance. Indonesian studies on potassium and magnesium recovery illustrate why site variation makes a universal injection formula inappropriate. If the baseline is severely under-fertilised, correcting dose and timing through ordinary management may deliver large benefits without an irrigation network.

Fertigation recipes must also be checked against biological recycling. Ground covers, palm frond piles, organic amendments and retained litter affect nutrient cycling and moisture conservation and should not be displaced simply because nutrients are available in

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liquid form. A hybrid schedule may supply particular readily soluble nutrients through the line while retaining other amendments through soil application. Importantly, improved nutrition did not uniformly buffer oil palm against water-related low-yield periods in multi-year Indonesian field trials; nutritional and hydrological interventions are complementary only under demonstrable conditions.

An Indonesian paired-block study in Lampung provides a useful caution about the relationship between fertiliser formulation and fertigation readiness. It compared a nitrate-based nitrogen-potassium compound with straight mineral fertilisers during a drought-affected observation period, but neither treatment used fertigation and the limited design does not establish generalizable treatment effects. Its relevance is therefore diagnostic: ingredient selection, labour requirements and realized farm returns should be appraised independently of whether nutrients are conveyed through an irrigation network.[49]

Prerequisite 3: a legitimate and dependable water supply

Source adequacy must be proven at the time of maximum need, not inferred from wet-season pump tests. Reservoir storage, seasonal river flow, groundwater recharge, canal conditions, competing abstractions, drought restrictions and legal access should be screened as a combined water-security prerequisite. Annual volumes alone miss timing mismatch: water can be abundant during storms and scarce during the dry weeks when a palm response is most likely. Projects without enforceable withdrawal arrangements and a defensible reserve for households and ecosystems cannot be classified as ready.

The watershed boundary matters because an estate can improve its own water productivity while reducing low-season water availability downstream. Indonesian basin modelling links oil-palm landscape conversion to runoff, sediments and nutrient loads, although those effects cannot be attributed to fertigation per se. Responsible planning should therefore state the abstraction source and maximum withdrawal, identify vulnerable users, and provide a transparent shut-off trigger for scarcity. The social value of irrigation cannot be assessed solely through FFB receipts if external users bear additional hydrological risks.

Prerequisite 4: suitable water chemistry and soluble fertilisers

A physically available source is not necessarily usable for precision injection. Screening should include suspended sediments, turbidity across seasons, pH, electrical conductivity, hardness, alkalinity, iron, manganese, microbial activity and potential biofilm growth. When relevant ions and fertiliser products are combined, precipitation may occur even if each is stable separately. The site should undertake water-product compatibility tests and small-scale injection trials, including flushing and cleaning protocols, before high-volume fertiliser contracts are signed. Emitter experiments with high-sediment water demonstrate interacting particulate, chemical and biological clogging pathways; a methodological review explains how these mechanisms may be diagnosed. Salinity-threshold and organic-fertiliser studies provide additional mechanism-specific, non-palm evidence.[50,51]

Recent experiments provide more specific evidence that water chemistry and nutrient formulation are coupled engineering variables. Wang et al.[52] evaluated combined physical and chemical influences on emitter clogging, identifying sediment characteristics and flow-path dimensions as important predictors; Ma et al. (2025) further demonstrated that nitrogen-fertiliser choice influences diaphragm aging and failure in pressure-compensating systems supplied with sediment-laden water. These controlled experiments clarify what field commissioning should test, but their equipment and water conditions cannot be regarded as representative of Indonesian oil-palm estates without site verification.

Product selection also changes operations. Concentrated calcium and phosphate solutions, some sulphate mixtures and particulate-containing organic liquids may require separate tanks, dilution or special injection sequencing to limit deposits. These are chemistry-dependent possibilities, not universal incompatibility rules; the actual fertilisers and water must be tested. In high-sediment conditions, cross-crop experiments show that fertiliser properties can materially change emitter fouling, so low sticker prices for soluble inputs are not sufficient evidence of low lifecycle cost. A documented compatibility matrix should be treated as a condition for moving to design procurement, with tests addressing particulate, chemical and combined equipment failure risks.

Prerequisite 5: hydraulic uniformity under field conditions

Effective performance requires water and nutrients to be delivered with acceptably uniform discharge across the actual block. Engineers must calculate pipe friction, elevation effects, pump curves, valve sectors, lateral lengths, injector mixing time and end-of-line flushing, then confirm them through measured outlet flows. Hydraulic designs developed without realistic field topography can overstate uniformity and underestimate pressure requirements.[53] Pressure-compensating-emitter failure studies show that in-situ deposits, pressure variation and multiple fouling pathways can undermine nominal uniformity.[54] Review evidence consequently supports repeated post-commissioning checks rather than relying on an initial acceptance test.

Oil palm poses an additional geometric challenge: the wetted bulb must overlap active uptake zones rather than simply wet an easily accessible strip beside each trunk. Emitter positions, number per palm, radius, depth, root activity, compaction and machinery traffic require field testing. Subsurface systems may reduce interference with field work but make faults harder to locate; long-term sugarcane investigations report root intrusion and multiple-fouling risks that merit testing in palms without assuming identical incidence. Uniform emitter discharge is only an intermediate process indicator; the decisive outcome remains effective root-zone supply and harvest response under site-specific palm water requirements.

Evidence from a five-year subsurface drip system in the North China Plain reinforces the difference between an initial commissioning certificate and durable field delivery. Li et al.[55] measured thousands of emitters and reported changes in flow characteristics, uniformity and deposits after extended operation; the underlying study concerned maize, not oil palm. The appropriate implication is to specify multi-year inspection and asset-replacement protocols rather than to borrow the reported uniformity or service life as an Indonesian plantation forecast.

Prerequisite 6: energy, maintenance and operator competence

The entire delivery chain must function during stress events. Pumps, motors, backwash units, valves, sensors and injector systems require reliable energy, fault detection, routine service, spare parts and authorised staff. The project should identify an accountable operator, preventive-maintenance frequencies, a repair-response standard and records of delivered water and fertiliser. Without these arrangements, a technically sound design may fail because an emitter clogs or a pump stops during a critical week. Studies of solar pumping and predictive irrigation control demonstrate engineering options for managing energy demand. Related solar and automated irrigation research provides supporting technology analogies, not oil-palm profitability estimates.

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Off-grid photovoltaic systems merit assessment where grid power is scarce, but their prerequisite assessment includes cloudy-period reliability, storage, conversion losses, theft risk, battery replacement and repair logistics. IoT control systems also require sensor calibration, communications support and a safe manual operating mode. Automation should prevent inadvertent dosing if flow or pressure falls outside specified ranges; it should not conceal poor hydraulic performance behind attractive dashboards. A staged commissioning program that validates manual and hydraulic control before adding remote optimisation is likely more robust than maximal automation from the outset.

Prerequisite 7: useful information and monitoring discipline

Sensors are decision aids only when their data are representative, calibrated and linked to a sound agronomic rule. Soil-moisture probes should be placed by soil and topographic strata, while leaf nutrient analysis and representative yields remain necessary to check machine-learning estimates. Remote sensing and UAV imagery can target sampling, detect heterogeneity and refine block selection, but vegetation indices do not directly quantify the appropriate soluble nutrient dose. Indonesian precision-oil-palm initiatives strengthen the case for integrated diagnostic systems while also demonstrating the need to validate prescriptions in the field.

Monitoring must support comparison rather than merely document operations. At minimum, a pilot should record rainfall, water abstraction, pumped volume, injected nutrient mass, uniformity, repair time, foliar status and standardised yield records. Data quality checks should flag sensor drift, missing harvests, inconsistent area boundaries and intervention dates. Without a transparent denominator, water-use efficiency and nutrient-use efficiency ratios can be improved statistically while absolute resource consumption or nutrient depletion worsens. Measurement protocols should therefore be established before the first treatment and applied equivalently to comparator plots.

Prerequisite 8: an optimised baseline and credible causal comparison

A weak control is perhaps the most overlooked prerequisite for claims of effectiveness. Comparing fertigation against irregular or insufficient fertiliser use can make any comprehensive management upgrade appear successful, obscuring the contribution of water application or nutrient delivery specifically. At least one comparator should represent optimised conventional nutrient and moisture-conservation practices. Where resources allow, treatments should separately test irrigation, corrected nutrient balance and fertigation, with equal nutrient targets and field-worker attention. Replication across representative slopes and soil classes is essential for attributing measured yield effects to the intervention rather than site selection. Nutrient imbalances in Indonesian smallholders and crop-specific fertigation comparisons reinforce the importance of distinct treatment controls, without demonstrating a mature-oil-palm fertigation premium.

The duration of evaluation should reflect perennial biological lags. Bunch initiation, sex differentiation, floral abortion and final bunch weight respond on different timescales, making a short trial prone to misinterpretation. Multi-season yield history and consistent recording of bunch number and average bunch mass help distinguish a treatment response from endogenous cycles and climate. Research on weather-driven oil-palm variability indicates why even a profitable-looking first-year response cannot justify general deployment. A useful trial should pre-specify its outcome hierarchy, effect sizes of practical interest and decision procedure for inconclusive results, with due attention to longer-term climate and nutrition interactions.

Prerequisite 9: credible incremental financial performance

The investment prerequisite concerns incremental, risk-adjusted net value, not total FFB sales from a plot equipped with fertigation. Costs include source access, permits, pumps, pipes, filters, emitters, fertilisers, electricity, maintenance, labour, training, failure and disposal. Benefits might include additional marketable FFB, reduced conventional application expense, better crop stability or lower input requirements. The comparison should subtract the performance of optimised conventional management and allow biological response delays. Remaining productive palm life and replanting dates constrain the period over which expensive fixed assets can earn a return; Indonesian yield-gap studies inform the optimised comparator, while coconut and solar-pumping economics remain indirect analogies.

Financial readiness further requires scenario stress testing. A design should remain defensible under plausible combinations of low FFB price, costly soluble products, repeated dry-season pump use, infrastructure failure and modest rather than optimistic yield uplift. Cooperative assets create additional questions about payment defaults, allocation of repair bills and residual ownership. An apparent positive net present value that omits water opportunity costs or deferred component replacement is not evidence of investment feasibility. Economic eligibility should be demonstrated through transparent, auditable cash flows before field expansion is approved.

Prerequisite 10: ecology, safeguards and institutional legitimacy

Environmental qualification starts with avoiding harm rather than promising that precision necessarily saves resources. Water withdrawal, nutrient loading, soil erosion, runoff and greenhouse-gas consequences can move in different directions. A lower application rate may reduce nitrate loss, but effects established in annual-crop syntheses should be interpreted cautiously under high tropical rainfall and oil-palm soils (Zheng et al., 2023; Fu et al., 2026). Independent monitoring and watershed safeguards should be specified before installation. Other global syntheses provide useful hypotheses for nitrogen losses and water-table management, not final Indonesian plantation emission coefficients.

Peat and flood-prone land require a separate screening logic. In peat ecosystems, subsidence and carbon emissions are linked to water-table control, so micro-irrigation may not address the most important ecological constraint. Research on drainage-level photosynthesis and peatland rewetting emphasises that the hydrological objective may differ fundamentally from that on drought-prone mineral soils. Flooded mineral-soil sites likewise may need drainage and oxygen management more than additional irrigation. These landscapes should not be pooled into a generic pilot suitability score, and certain interventions should be explicitly ruled out where they conflict with environmental protection.[56]

Institutional prerequisites vary by adopter type. Large estates can potentially centralise laboratories and technicians, while independent smallholders may need cooperative purchasing, shared water rights, service contracts and patient financing. Farmer studies show that even ordinary fertiliser use may be limited by money, availability and logistical constraints; a capital project that leaves these unresolved risks widening yield and income gaps. Credible readiness requires evidence of accountable governance, transparent cost sharing, grievance handling, inclusive water allocation and a viable technical support provider long after an external pilot ends.

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Integrating the findings

The prerequisites interact rather than form ten independent checkboxes. Water deficits can create agronomic opportunity but also exacerbate community water competition; reliable pumping makes delivery feasible but increases capital and energy requirements; a fertiliser that solves a nutrient shortage may clog emitters when mixed with local water. Technology readiness is therefore constrained by its weakest essential link. Figure 1 explicitly locates all ten prerequisites in four non-substitutable domains: agronomic necessity (P1–P2), technical deliverability (P4–P7), comparative evidence and economics (P8–P9), and water and institutional legitimacy (P3 and P10). The framework does not estimate the national proportion of plantations that satisfy these conditions; that must be measured through site assessments informed by spatial targeting, nutrient diagnosis, engineering reliability and watershed safeguards.

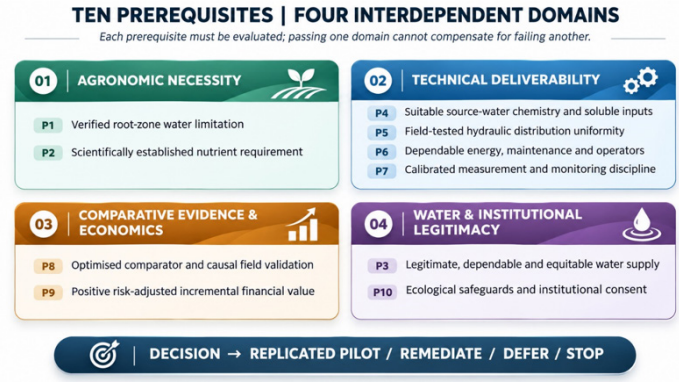


Figure 1 Ten prerequisites mapped explicitly to four domains. Original digitally composed schematic produced; no photographs, stock images or third-party graphics were used.

Figure 1 should be interpreted as a set of jointly necessary conditions, not a ranking of which input has the highest average benefit. Water-source legitimacy (P3) is placed in the governance domain even though its dependable quantity and timing also constrain technical operation; that cross-domain dependence is deliberate. A project can satisfy the engineering row yet fail the water-rights row, or demonstrate a yield increment yet fail the investor's risk-adjusted hurdle. Such mismatches are legitimate reasons to defer or reject implementation. A readiness diagnosis should identify which constraint can be solved cheaply and which is structural, thereby preventing sunk-cost escalation as sophisticated components are added to a weak basic proposition.

Discussion and analysis

Prerequisites as a weakest-link production system

The central synthesis is that effective fertigation depends on four non-substitutable dimensions: biophysical need, reliable delivery, defensible incremental value and social-environmental legitimacy. An excellent hydraulic design cannot compensate for the absence of water stress, and favourable root-zone moisture cannot compensate for unresolved downstream claims. This framing challenges technology adoption narratives that assume higher precision automatically enhances sustainability. In a perennial plantation, such claims require particular caution because intervention costs are front-loaded and production responses can take years to materialize.

The weakest-link argument also changes the order of investment. A conventional agronomic diagnostic and a water-source assessment should precede detailed pump procurement, while a simple pump-and-filter prototype should precede costly telemetry. If a site cannot prove a sustainable water source, later engineering refinements are largely irrelevant. If it cannot establish a balanced nutrient prescription, a chemically flawless dosing system may efficiently distribute the wrong mixture. More advanced decisions therefore depend on successful completion of previous evidence-generating steps rather than the presence of a predetermined capital budget.

Identify candidates by need and readiness, not estate size

Figure 2 converts the weakest-link interpretation into a site-screening matrix using biophysical opportunity and implementation readiness. High need with high readiness supports a controlled pilot; high need with low readiness supports investment in the missing prerequisite rather than premature installation. Low need with high readiness favors optimization of nutrient management without irrigation, whereas low need with weak readiness directs limited resources to basic agronomy. These categories are conceptual decisions; they are not claimed to be statistically validated classifications of Indonesian estates or independent smallholders.

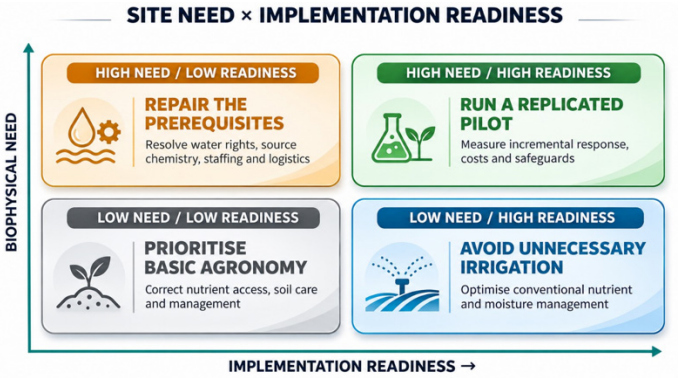


Figure 2 Conceptual suitability matrix distinguishing agronomic need from implementation readiness. Original digitally composed schematic produced; no photographs, stock images or third-party graphics were used.

The matrix is deliberately asymmetric. It does not assume that strong financial and technical capacity makes irrigation rational when the crop does not need it, nor that observed drought means water abstraction is automatically permissible. An additional ecological exclusion screen must override apparently favourable positions if the source threatens communities, peatland integrity or protected ecological flows. The matrix should be populated with locally observed inputs and transparently documented reasons, allowing sites to move between categories after management changes or stronger evidence.

Establish the optimised counterfactual first

The counterfactual determines whether an experiment answers a useful managerial question. Where existing fertiliser management is deficient, equalizing plant nutrients through optimised conventional spreading may close a substantial share of the yield gap. If fertigation also receives extra technical supervision, improved harvesting or better road access, the treatment confounds managerial upgrading with equipment effects. Studies of smallholder agronomic performance make this concern particularly relevant to Indonesia. The preferred interpretation is therefore incremental: What additional result is produced by integrating water and soluble nutrients after the practicable low-cost corrections have been undertaken? The comparator should account for established soil-health and understory management approaches.

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The trial should ideally allocate representative, matched blocks to current practice, optimised conventional nutrition, supplemental irrigation without nutrient injection, and fertigation with equivalent nutrient targets. A hybrid nutrient treatment can be added where nutrient solubility or cost makes complete fertigation unrealistic. The design may require adjustment for available field scale, but deviations should be documented so that no one mistakes a bundled management package for a pure fertigation response. The analytical burden is substantial, yet it is less costly than deploying unproven hardware on thousands of hectares.

Translate root-zone mechanics into engineering specifications

A palm-focused hydraulic specification should begin from the intended wetted soil volume and measurable uptake zones. Emitter count and spacing ought to be tested at representative palm ages and soils before the network is scaled. Soil texture, slope, preferential flow and compaction affect whether delivered solution moves laterally into active roots or bypasses them into deep drainage. This makes a plant-soil-water field experiment a prerequisite for reliable full-block pipe calculations, rather than an optional validation after installation.

A design should document operating pressures under the lowest and highest expected reservoir levels, start-up and shutdown transients, injector mixing and fertiliser residuals, filter differentials and the frequency of end flushing. Regular audits of emitter output should be required because hydraulic uniformity and fertiliser uniformity can deteriorate in different ways. Lessons from laboratory and subsurface systems indicate multiple failure pathways, but plantation-specific endurance data remain a priority. A high-quality supplier submission must make maintenance and fault isolation auditable, not merely provide a hydraulic simulation performed at ideal initial conditions.

This specification should also distinguish water-application uniformity from nutrient-concentration uniformity. Research on prolonged subsurface operation and the joint effects of sediment and fertiliser composition indicates that stable nominal emitter discharge need not demonstrate identical root-zone nutrient exposure over time. Accordingly, validation should sample both emitter flow and solution concentration across near and distant positions, and should record whether flushing and service interventions restore performance under field conditions.

Treat water-source consent as an operating licence

Water-rights due diligence should be integrated with economic design. An apparently inexpensive canal source may become unavailable precisely during drought; a large reservoir may impose storage, sediment and land costs; a groundwater source may raise recharge and stakeholder concerns. Source selection thus affects technical continuity, legal exposure, private cost and social legitimacy simultaneously. Managers should undertake dry-season field measurements, document existing users and specify maximum acceptable abstraction prior to engineering tender. This procedure reduces the risk that installed assets become stranded or a technical success becomes a watershed conflict.

The ecological screen should incorporate water quality as well as quantity. Where irrigation enables more frequent nitrogen application, managers must track whether it reduces surplus or merely shifts the season and location of loss. Meta-analyses in other agricultural systems report benefits for some nitrogen pathways but also demonstrate that the response is comparator- and context-dependent. On Indonesian catchments with erosion and sediment burdens, water accounting should encompass surface runoff and downstream conditions rather than rely exclusively on the applied irrigation volume per kilogram FFB.

Choose a service model before specifying automation

Technology selection cannot be separated from the identity and skills of its operator. Estates may have pump mechanics, agronomy laboratories and procurement systems, while dispersed smallholders may depend on itinerant service providers or a cooperative technician. A system that requires daily specialist intervention may be unacceptable even where its theoretical yield benefit is large. The service model should define spare-parts holding, training, maintenance tariffs, downtime responsibility, incident reporting and safe operation under sensor failure. These details are prerequisites for reliability and equity rather than implementation matters to be decided after purchase.

Data systems can be added progressively once a reliable manual baseline is in place. Satellite- or UAV-based nutrient indicators may identify blocks needing investigation, while calibrated probes may govern irrigation timing. A platform should nevertheless be designed to accept human correction, flag improbable readings and retain a usable audit trail. Automatic fertiliser injection should stop under abnormal flow, and the system should remain repairable with local skills and conventional parts. Simplification can therefore improve readiness even if it reduces the number of digital features advertised by a vendor.

Set a rigorous investment hurdle

A transparent investment appraisal should compute incremental net present value relative to the optimised alternative. Let ΔR_t denote additional net FFB revenue at year t, ΔS_t avoided conventional operating costs, ΔO_t incremental operating cost, ΔX_t equipment replacement and risk expense, K_0 upfront investment, r the annual discount rate, T the remaining project horizon, and V_T any realizable terminal value. The risk-adjusted decision metric is defined by Equation (1), in which future net differences are discounted to their present value.

$$\Delta \mathrm{NPV} = -K_0 + \sum_{t=1}^{T} \frac{\Delta R_t + \Delta S_t - \Delta O_t - \Delta X_t}{(1+r)^t} + \frac{V_T}{(1+r)^T}$$

Equation (1). Incremental project net present value (illustrative decision expression).

This expression clarifies cost categories but provides no observed Indonesian NPV without field records and quoted prices. Estimating the parameters is a separate empirical task; only transparent comparison with the optimised baseline can support an investment decision.

Projects should report a breakeven yield increment for each scenario, noting that the effective FFB margin is not the same as gross farm-gate price when extra bunches require harvesting and transport. Testing should include different drought recurrence, discount rates, energy prices, soluble-fertiliser premiums, repair frequencies and productive palm lives. If returns depend on a percentage yield gain borrowed from maize, wheat or coconut studies rather than measured oil-palm performance, the project has not passed an evidence-based investment hurdle. Modelling uncertainty must remain visible rather than compressed into an apparently precise single payback year.

Financial models for shared smallholder systems require separate rules for contributions, collection, sanctions, conflict resolution, access for marginal farms and component ownership. Aggregating plots can lower fixed cost per hectare but also creates a collective-

action problem around water allocation and maintenance. When credit availability already determines ordinary fertiliser use, tying farmers to unfamiliar debt without measured agronomic increments may be inequitable. The principal policy priority is then building agronomic diagnostics and feasible credit rather than subsidizing visible irrigation machinery.

Apply a differentiated approach to mineral soils, peat and floodplains

The review does not advocate a single national eligibility rule. Mineral-soil blocks with shallow storage, demonstrable dry-season deficits and accessible low-risk water are plausible candidates, subject to economic and engineering tests. Sandy soils may need different pulsing intervals and filtration strategies from heavier soils, while compacted blocks may benefit first from rehabilitation. In peat and frequently flooded settings, managing drainage, oxygen, subsidence and water table can be the primary task. Introducing fertigation without a landscape hydrological diagnosis could add cost while failing to address the actual constraint.

The same differentiation is needed across palm age and replanting strategy. Nurseries present controllable root-zone volumes and short interventions, whereas mature palms integrate water and nutrient responses across a much larger rooting environment and delayed crop-development processes. Consequently, positive nursery outcomes support local experimentation but should not be presented as evidence of mature estate-level yield increments. A mature stand scheduled for replanting may have too little time to amortize fixed infrastructure even if a physiological response is plausible.

Link the prerequisites to a phase-gate rollout

Figure 3 presents a proposed implementation sequence. Gate 1 confirms water stress, soil conditions, plant nutrition and an optimised conventional baseline; Gate 2 resolves secure supply, water governance and ecological exclusions; Gate 3 validates product chemistry, hydraulic geometry and maintainability; Gate 4 undertakes replicated multi-season comparison; Gate 5 audits cost and operational performance; and Gate 6 authorizes selective scaling under ongoing reporting. Each gate can yield a proceed, redesign, defer or stop decision rather than treating completion of the project as inevitable.

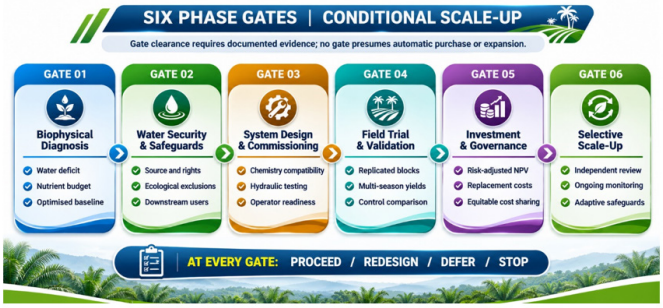


Figure 3 Proposed six-gate pathway with proceed, redesign, defer and stop options. Original digitally composed schematic produced; no photographs, stock images or third-party graphics were used.

A gate system is valuable because it makes learning explicit and reversible. Poor early results need not signal program failure if they prevent a larger stranded investment, and a technically sound pilot need not be scaled if its environmental costs or financial risks are unacceptable. The sequence should be subject to independent review with documented criteria, including periodic reassessment when water rights, drought patterns, fertiliser prices or management capacity change. Such a design separates public research value from the commercial obligation to proceed with equipment procurement.

Research, standards and policy implications

Indonesia needs coordinated field trials across climate and soil domains, explicitly reporting water balance, root-zone distribution, fertiliser mass, annual FFB, bunch components, maintenance and social effects. Shared reporting definitions would make independent experiments more informative than many proprietary demonstrations using different outcome measures. Laboratories and universities can support nutrient and water-quality testing, while independent engineering audits can verify uniformity and service durability. Long-term research should examine whether improvements in resource efficiency persist after equipment wear, personnel changes and repeated weather anomalies.

Public support should target prerequisites that benefit many producers, such as field diagnostics, transparent water availability data, training and access to credible agronomic advice. Performance-contingent financing could encourage rigorous pilots without socializing the costs of premature estate-wide deployment. Certification and sustainability programs may strengthen safeguards, yet evidence of uneven smallholder participation cautions against assuming that institutional labels guarantee effective water allocation or maintenance. Technology-neutral extension better respects the possibility that conventional best practices outperform fertigation in particular places.

Theoretical contribution and remaining gaps

This review contributes a prerequisite theory of agricultural precision technology in which usefulness arises from alignment among biological demand, material delivery, institutional rights and longitudinal evidence. It avoids a binary debate over whether fertigation works by asking what must already be true for it to work and who is capable of sustaining those conditions. The framework can be tested by relating independently assessed site readiness to subsequent operational reliability, measured agronomic increments and environmental indicators. Its value lies in articulating refutable conditions rather than asserting universal benefits in advance.

Important evidence gaps remain. Published crop-specific effect sizes from annual-crop fertigation cannot resolve mature-palm emitter placement, delayed FFB response, year-round rainfall interaction or estate-scale cost structures. Research must also address water allocation and gendered or distributional consequences in smallholder cooperation, particularly where downstream communities rely on dry-season flows. Until multi-site and multi-season Indonesian studies become available, the prerequisite matrix is a defensible guide for evaluation, not an empirical certification standard with validated numerical cutoffs.[57–64]

Conclusion and recommendations

The effective implementation of fertigation in Indonesian oil palm depends on proving a relevant agronomic need and satisfying a set of interdependent preconditions rather than merely installing irrigation equipment. The strongest candidates are sites with recurring, measured water deficits and a correctable nutrient-delivery problem; even these candidates require secure water, compatible fertilisers, reliable hydraulics and competent operators. The evidence does not support treating results from annual crops or different palm species as fixed performance forecasts for Indonesian mature oil palm. A decision to defer or reject fertigation can be both economically rational and environmentally responsible.

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The practical starting point should be a documented baseline of rainfall, soil water, leaf nutrition, fertiliser practice and FFB yield. Managers should first correct low-cost problems in nutrient balance, harvesting, soil cover and moisture conservation, then test whether irrigation and soluble injection provide a further advantage. Field designs must be checked against active uptake zones, seasonal water chemistry and genuine maintenance capacity. Complex automation should be introduced only after reliable manual and hydraulic operations have been demonstrated.

The financial prerequisite is a positive risk-adjusted incremental return over an optimised feasible alternative, evaluated over the remaining productive life of the palms. Estimates should account for water access, energy, filtration, labour, soluble-input premiums, system failures, replacement and delayed yield effects. Water-sharing and debt arrangements must be transparent, particularly when adoption depends on cooperative infrastructure or smallholders. A favourable private calculation is not sufficient when water withdrawals, peatland impacts or community risks violate environmental safeguards.

An appropriate implementation policy is therefore phased, conditional and technology-neutral. Managers and policymakers should fund diagnostic capacity, openly reported comparative trials, training, and enforceable water governance before financing broad infrastructure expansion. Coordinated Indonesian field research must establish reliable response parameters across soil classes, rainfall regimes, palm ages and ownership models. The principal finding is a readiness condition: scale fertigation only after the complete chain from biological necessity to maintainable delivery and equitable, verified benefits has been demonstrated.

Declarations

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Competing interests

The author confirms that the author has no competing interests to declare.

Data availability

No original field, laboratory, interview, permitting or commercial cost dataset was generated for this qualitative literature review. Its documentary evidence is identified in the reference list. The original search-screening log was not preserved, and no associated numerical screening dataset is claimed.

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