ISSN: 2634 - 8845

Journal of Earth and Environmental Science Research

SCIENTIFIC Research and Community

Research Article

Open Access

Beyond Oil Palm Monoculture: Phase-Specific Multicropping, Livestock Integration and Inclusive Value Chains for Sustainable Plantation

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ABSTRACT

Oil palm landscapes are central to rural livelihoods in Indonesia, yet production systems face interacting concerns about ecological simplification, ageing palms, yield gaps, income volatility and uneven market participation. Diversifying land use within established plantations has been proposed as a pathway towards environmental, social and economic sustainability, but its feasibility varies substantially between immature and mature plantation phases. This qualitative literature review synthesises peer-reviewed research published during 2020–2026, examining intercropping, managed understorey vegetation, crop–livestock integration, smallholder livelihoods, ecological restoration and value-chain governance. Using an interpretive thematic approach rather than a systematic review or meta-analysis, the article distinguishes direct oil-palm evidence from transferable findings in other agricultural systems. Six linked themes emerge: phase-dependent biophysical suitability; conditional ecological multifunctionality; livestock feed and biosecurity constraints; profitability and household risk; seed, labour and offtake bottlenecks; and institutional capacity. The proposed phase-specific decision architecture prioritises food and horticultural crops during the immature stage, and carefully managed understory forage or livestock options during the mature stage, subject to site assessments. Diversification alone is neither a guaranteed yield gain nor an adequate substitute for forest protection, sound palm agronomy or equitable contracts. A market-first, pilot-before-scale programme with measurable ecological safeguards, enterprise budgets and negotiated benefit sharing provides a more defensible implementation pathway. The review identifies comparative trials and longer-term socioeconomic monitoring as priorities for validating landscape-level sustainability gains.

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Received: October 16, 2026; **Accepted:** October 22, 2026; **Published:** October 31, 2026

Keywords: Oil Palm, Multicopying, Intercropping, Integrated Crop–Livestock Systems, Oil Palm Smallholders; Agroforestry, Ecosystem Services, Rural Livelihoods, Inclusive Value Chains, Indonesia

Jel Classification: Q12, Q15, Q18, Q56, O13

Introduction

The Production–Sustainability Dilemma in Indonesian Oil Palm Landscapes

Oil palm has simultaneously contributed to agricultural income and generated extensive debates about land conversion, forest integrity and the distribution of development benefits. These outcomes cannot be represented by one average plantation: a recently replanted smallholding, a mature industrial estate and a plantation on hydrologically sensitive peatland have different constraints, management possibilities and sustainability baselines. The challenge is therefore not simply to replace monoculture with a greater number of commodities, but to identify spatially and temporally appropriate modifications that improve aggregate benefits without shifting costs to soils, remaining forests or vulnerable households. Recent analyses of expansion, certification and livelihood security underline the importance of respecting this heterogeneity A compelling opportunity arises during the immature oil palm phase, locally termed tanaman belum menghasilkan (TBM), when young palms have not yet begun commercially meaningful fresh-fruit-bunch production. Wider spaces and higher ground-level irradiance may allow some annual or short-duration crops, provided they do not compromise palm establishment or soil management. Once the canopy develops during the tanaman menghasilkan (TM) phase, light competition, palm root occupation and operational access change the available options. Treating intercropping as a continuous, uniform land-use practice risks overlooking the dynamic nature of an oil palm rotation, especially among households already facing replanting-related cash shortages the initial stakeholder concept presentation motivating this review makes that phase distinction explicit. It proposes maize, pineapple, watermelon and banana as potential TBM intercrops, while associating mature plantations with selected forage species, goats or sheep, and ducks. Its complementary proposals include collaboration among communities, government and firms; access to high-quality inputs; labour development; offtake arrangements; and coordination of supply with demand. Importantly, the initial literature advances these ideas as implementation concepts, not as published field trials demonstrating their yields, causal effects or financial returns. A credible academic synthesis must therefore distinguish those candidate activities from independently tested outcomes and make explicit where site-specific validation remains necessary [1-10].

Why a Broader Integrated-Production Perspective is Needed

The appeal of diversification is supported by a growing body of evidence demonstrating that appropriately designed agricultural diversification can enhance some ecosystem services and

resilience attributes. Cross-system syntheses report positive but variable effects on biodiversity, soil processes, pest regulation and profitability, although positive mean outcomes should not be converted into unconditional predictions for Indonesian palm plantations. A plantation can support richer ground vegetation without being comparable to a natural forest; an additional crop may increase gross production while reducing net profitability after accounting for labour, inputs and marketing losses. Consequently, an integrated framework must evaluate both synergies and substitution effects against a clearly defined baseline An overly narrow agronomic treatment may also underestimate institutional constraints. Many independent smallholders encounter uneven access to agronomic advice, insufficient or imbalanced nutrient inputs, land documentation problems, limited bargaining power and high transaction costs for compliance and marketing. Additional crops or livestock can intensify these burdens unless complementary business services are arranged. Studies of palm certification highlight that improvements linked to organisations and management support cannot simply be attributed to a sustainability label; financial incentives, administrative requirements and who bears compliance costs all matter. Similarly, the benefits of new crops depend on credible buyers rather than optimistic assumptions about saleable harvests survey of 205 oil palm farmers in Jambi likewise showed that perceived practical difficulty and risk were important barriers to intended adoption of oil palm agroforestry, indicating why technical training and perceived control should feature in any partnership model [11-19].

Research Gap, Questions and Contribution

The relevant academic evidence is fragmented across intercropping experiments, general diversification meta-analyses, palm agronomy studies, cattle-grazing reviews, ecological-restoration experiments and social-science analyses of market governance. These bodies of research use different outcomes, counterfactuals and time horizons. Some measure species richness, others estimate palm yields or household profits, and still others examine certification or land-tenure conditions. As show for wider agricultural trade-off analysis, limited attention to cross-scale outcomes and uncertainty can cause an apparently attractive option to conceal important losses elsewhere. A context-sensitive interpretive synthesis is therefore needed before recommending scaled investments in multicropping programmes [20].

This review addresses six questions: how TBM and TM conditions affect option suitability; which ecological benefits and trade-offs are demonstrated; when diversification improves incomes or employment without damaging palm performance; how labour, seeds, tenure and markets shape feasibility; which biological and commercial risks require safeguards; and which institutional design can support responsible implementation. Its distinctive contribution is a phase-specific, three-gate decision architecture combining biophysical fit, business viability and governance legitimacy. The synthesis is deliberately analytical rather than a claim to new field data, and it treats oil-palm-specific evidence as more directly applicable than global extrapolation. The resulting framework can guide comparative pilot design, private–community partnerships and policy evaluation [21,22].

Literature Review

Ecological Intensification, Complementarity and Agricultural Diversification

Ecological intensification seeks to use biological interactions and ecosystem processes to support production and environmental outcomes, rather than relying exclusively on additional external inputs. In a mixed cropping system, such interactions may include different rooting profiles, seasonal resource partitioning, ground-cover protection or habitat provision for predators of agricultural pests. Yet species richness alone does not guarantee positive interactions; poorly matched crops may compete for the same light, moisture or nutrients. Studies of intercropping performance emphasize that resource complementarity depends on planting design, species combinations and timing, while broader diversity–productivity research reveals substantial environmental variation in the magnitude of benefits For oil palm, complementary production should be assessed using both palm-equivalent and whole-farm outcomes. The land equivalent ratio (LER) can compare the area required under reference sole-crop systems with that used by an intercrop, but its valid calculation requires observed component yields and suitable sole-crop controls over a comparable period. This metric is especially tricky when one component is a perennial palm and another is a seasonal food crop, because immature and mature phases do not provide equivalent palm yields or land-use opportunity costs. A positive aggregate LER must not conceal reduced palm performance in later years, heavy unpaid family labour or degradation of vegetation management around harvesting paths Where TBM plantations produce no harvestable palm output, the palm-yield denominator in a conventional LER comparison may be zero; the metric must therefore not be calculated mechanically for that period. Phase-adjusted enterprise cash flow, observed component yields and subsequent palm establishment are more interpretable outcomes until compatible sole-crop controls exist. Agricultural diversification has similarly been associated with enhanced ecosystem functioning through soil cover, structural complexity and habitat heterogeneity. A systematic evidence synthesis reported that diversification can improve multiple ecosystem services without necessarily reducing yield, while a meta-analysis found beneficial outcomes to be highly variable across crops and settings. More recent long-horizon synthesis suggests that profitability and ecological benefits can coincide, but differences in baseline management and observation period are material. These findings provide useful mechanisms and hypotheses; they do not establish that a specific crop planted between oil palms in Sumatra or Kalimantan will deliver a positive net return [23].

Palm Developmental Stage as an Ecological Constraint

Young oil palm stands initially leave relatively open strips between palms, but their architecture and light interception change progressively as fronds expand. Therefore, the feasibility of maize, watermelon or pineapple differs across plantation ages, row geometry, soil fertility, water availability and the restrictions needed for palm maintenance. Evidence that agronomic practices explain considerable yield gaps in smallholder oil palm fields indicate that intercropping plans should protect rather than displace fertilisation, weed control and crop monitoring. Moreover, documented nutrient deficiencies and imbalances mean that intercrops cannot be assumed to feed themselves from unused soil resources [24,25].

The mature-plantation understorey is an alternative setting rather than an inferior version of TBM cropping. Mature palm canopies restrict available sunlight yet provide microhabitats for some shade-tolerant ground vegetation, legumes and managed forage. Evidence from Indonesian smallholdings associates understorey vegetation with aspects of soil health, while biodiversity studies demonstrate that undergrowth characteristics can influence butterflies, arthropods and pest-control interactions. Such relationships are not necessarily linear: highly cleared understories

can undermine habitat provision, whereas unmanaged competitive vegetation can interfere with field access or crop operations. Site-specific vegetation regimes are therefore more defensible than universal prescriptions for either clearing or preservation Complementary Indonesian panel-data research found no statistically significant positive yield association for several nature-based management practices once relevant inputs were controlled, reminding practitioners that plausible ecological mechanisms must not be equated with demonstrated gains in fruit production [25-29].

Crop–livestock Integration and Circular Resource Use

Integrated crop–livestock systems seek to close resource loops through forage production, manure recovery, biological nutrient cycling and the complementary use of labour or machinery. Reviews across agricultural environments identify potential efficiencies, improved risk diversification and food-security contributions, but they also identify management complexity, health risks, environmental burdens and uneven institutional readiness. These findings should be used as a conceptual bridge, not evidence that a goat, sheep or duck enterprise will necessarily be profitable within any Indonesian palm plantation. Flock size, stocking rate, breed, water supply, veterinary access, shade tolerance, forage quality and household skills need to be evaluated independently Cattle deserve especially careful treatment because of divergent practical opinions about livestock within oil palm. identify genuine opportunities for grazing to use understorey resources, reduce some weed-management costs and generate livestock income, but also warn that forage becomes less available in ageing plantations and that evidence about longer-term palm yield responses is weak. The initial concept presentation discourages cattle on the grounds of potential palm and root damage and disease concerns; those warnings are relevant risk-screening inputs, not proof that cattle integration is universally inappropriate or that cattle cause Ganoderma infection. The analytically responsible position is to distinguish cattle-based models by plantation management, stocking intensity and biosecurity controls, while not making cattle the default recommendation for the proposed smallholder-oriented pilot [30,31].

Ecosystem Services, Restoration and Landscape Limits

The oil-palm literature increasingly evaluates sustainability in terms of multiple interacting ecosystem functions rather than the number of crops harvested. A large-scale experiment in Sumatra found that planted tree islands increased several biodiversity and ecosystem-functioning indicators without lowering yield at the overall plantation scale studied. Other work argues for ecological set-asides and landscape restoration in production mosaics, while research in palm landscapes identifies landscape heterogeneity and soil biota as important components of biodiversity recovery. Such results support deliberate multifunctionality, although a planted tree island is not equivalent to a cash-crop intercrop, and the same carbon or biodiversity gains should not be attributed indiscriminately to all agricultural diversification models Trade-offs also arise beyond the field boundary. The conversion of primary or regenerating ecosystems into oil palm cannot be justified merely because the ensuing plantation carries companion crops. Expansion into carbon-rich forests raises emissions and biodiversity concerns that intercropping cannot erase. On peat soils, water-table management and peat conservation often dominate the carbon balance; research on rewetting identifies potential emissions reductions that require a distinct hydrological intervention. Agroforestry carbon findings from India and West Africa may inform hypotheses about vegetation cover and biomass, but their climate benefits should not be transferred into Indonesian peatland systems without comparable carbon accounting and land-use baselines [32-37].

Livelihood Theory, Transaction Costs and Inclusive Value Chains

A sustainable-livelihood perspective recognises that households combine natural, human, financial, social and physical assets under conditions of uncertainty. For a replanting household, early crop cash flow may smooth expenditure during the period before fruit-bearing, but higher gross revenue is not synonymous with improved welfare. Households may face seasonal labour bottlenecks, new debt, unsold perishable produce, and unequal exposure to quality rejection. Indonesian evidence links oil palm to welfare outcomes while also identifying exposure to economic risk, highlighting the need to examine both mean incomes and downside events Value-chain governance determines whether extra farm output becomes realised value. In fragmented smallholder landscapes, perishable crops are sensitive to procurement schedules, grading, cold-chain gaps, transport and trader bargaining power. Collective marketing and prearranged buying can reduce some transaction costs, yet contracting may create new dependencies where prices are opaque or farmers lack exit options. Certification studies demonstrate that administrative burdens and external facilitation can substantially affect participation and realised rewards; these insights are transferable to multicrop partnerships, even though a certification scheme is not the same as a fruit or livestock marketing arrangement A long-running Indonesian farmer-organisation case further demonstrates that collective action and replanting resilience are shaped by interacting institutional, socioeconomic and biophysical conditions, rather than organisational membership alone [38-41].

Methods: Qualitative Literature Review

Review Design and Epistemic Orientation

The study adopts an interpretive, integrative qualitative literature review (QLR). Its objective is to organise heterogeneous recent findings into a coherent explanatory argument and applied decision framework, not to estimate pooled treatment effects or construct a statistically exhaustive sample of all publications. The method is therefore distinct from a systematic literature review, even though existing systematic reviews and meta-analyses can serve as substantive sources. The unit of analysis is the claim–context relationship: a reported outcome is interpreted alongside its crop configuration, plantation maturity, land tenure, climate, research design and measurement horizon. This approach is especially relevant where an economic case, an ecological experiment and a livestock review illuminate different parts of the same implementation problem The topical scope encompasses intercropping and multicropping, soil and understorey management, integrated livestock production, landscape biodiversity, smallholder replanting, agricultural enterprise risk, and market or institutional governance. Indonesian oil palm is the central application setting. Research from other countries or production systems is admitted where it helps explain ecological mechanisms or governance design, but it is explicitly classified as indirect evidence. The publication window of 2020–2026 prioritises current scholarship while acknowledging that foundational concepts predate the window. The initial concept presentation serves as a contextual source for identifying candidate interventions, not as a substitute for peer-reviewed outcome evidence [42].

Discovery, Appraisal and Evidence Classification

The preliminary literature pool was developed around combinations of terms such as oil palm, immature plantation, understorey, replanting, intercropping, integrated crop–livestock,

agricultural diversification, soil health, biodiversity, value chain and smallholder. The source base emphasises peer-reviewed international journals indexed by major scholarly publishers and includes primary field studies, reviews, social-science analyses and selected methodological syntheses. Citations are retained when they substantively contribute to the argument, and journal DOI links are provided for traceability. Because the process was designed as a QLR, no exhaustive retrieval claim, full-database census, numerical screening flow or PRISMA diagram is asserted This review did not apply a preregistered search strategy or claim comprehensive retrieval; selection was purposive, prioritising relevance, methodological transparency and direct applicability to Indonesian palm contexts. The interpretive process therefore supports conceptual transfer and identification of research gaps, while leaving formal effect-size estimation and publication-bias testing outside its scope. Evidence was appraised qualitatively on relevance, design transparency, ecological comparability, timescale and potential external validity. Directly observed oil palm results in Indonesia were treated as relatively proximate evidence for field-specific claims; oil palm evidence from another geography was interpreted conditionally; global reviews of diversification provided broader mechanistic context; and proposed interventions without trials were classified as hypotheses requiring evaluation. Disagreements were retained rather than smoothed away, especially where a production benefit measured at one scale coexists with costs or biodiversity impacts at another. This judgment-based synthesis supports cautious explanation but cannot establish the absence of publication bias or provide certainty equivalent to a systematic review

Thematic Analysis and Limitations

A deductive thematic scaffold was constructed from the original proposal's three sustainability pillars and operational constraints; it was refined inductively as the literature revealed phase-specific competition, ecological restoration limits, livestock management uncertainty and distributive concerns. Six themes organise the results: TBM crop suitability, TM forage and livestock suitability, ecological multifunctionality, enterprise economics, bottlenecks in labour and markets, and governance arrangements. Cross-theme synthesis then asks which combinations are mutually reinforcing, which involve unavoidable trade-offs and which lack empirical validation.

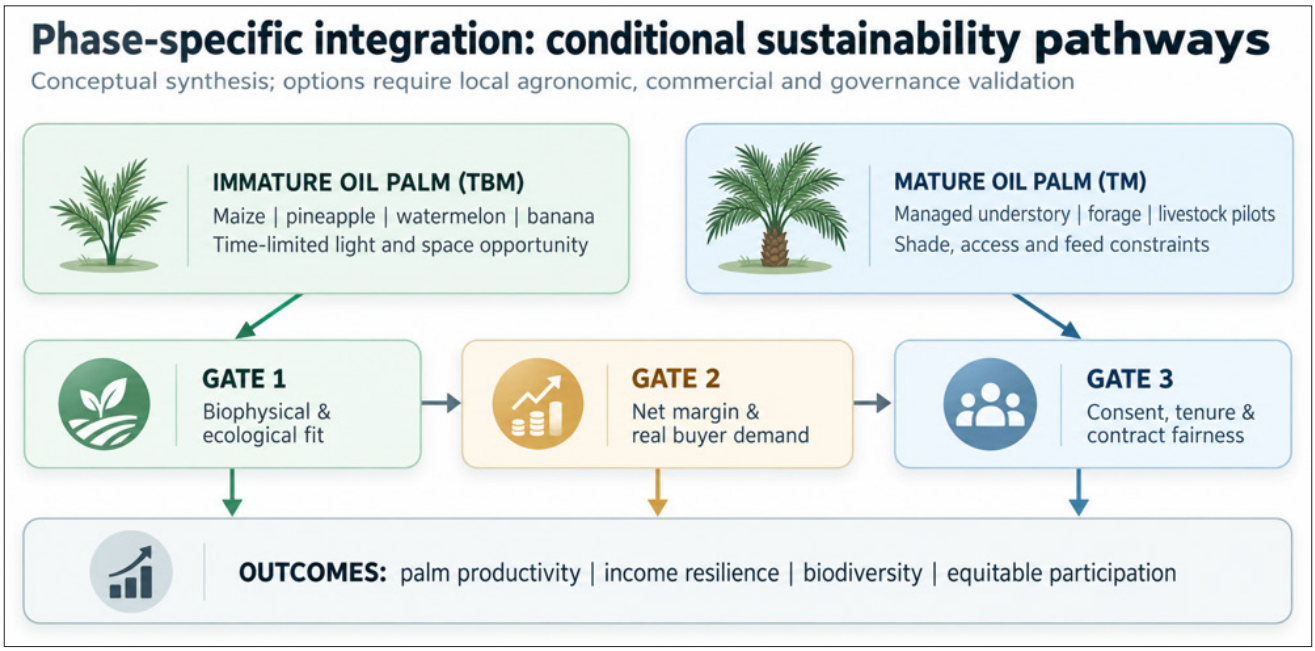


Figure 1: Phase-specific, three-gate conceptual framework for multicrop and livestock integration in Indonesian oil palm landscapes. Author-developed synthesis.

Figure 1 Introduces the Conceptual Architecture, While Subsequent Figures Connect These Themes to Implementation Choices.

Figure 1 is a conceptual map rather than a fitted causal model. It specifies the logic by which plantation phase shapes plausible production options, while land suitability, business capacity and institutional legitimacy jointly govern adoption. Treating these requirements as concurrent gates avoids the mistake of evaluating agronomic feasibility separately from marketing or tenure security. The feedback arrow represents the need to update management decisions when monitoring reveals palm-yield losses, low livestock welfare or unexpected price volatility; it does not imply that feedback mechanisms have already been tested in the proposed intervention sites.

Results: Thematic Findings

TBM Intercropping Creates a Temporary, Heterogeneous Production Window

The first theme is temporal opportunity rather than permanent land availability. During TBM, spaces between palm rows and relatively open light conditions can accommodate crops whose harvests occur before major canopy closure. Maize, pineapple, watermelon and banana, proposed in the initial concept presentation, represent markedly different systems: maize and watermelon can produce shorter cash-flow cycles, while pineapple and banana require different establishment periods, disease management, labour profiles and market arrangements. These are candidates for field screening, not four universally suitable intercrops. Soil type, slope, precipitation, drainage, row spacing, palm age, fertiliser placement and the machinery needed for replanting all determine how much usable space remains. Evidence from broader intercropping studies supports selecting

combinations by resource complementarity rather than commodity count A recent mixed-method study of privately owned peatland farms in West Kalimantan identified heterogeneous diversification decisions and reported that agroforestry practitioners may obtain greater food-security flexibility despite lower total incomes. The findings are direct contextual evidence of farmer choices, not proof that all proposed intercrops are productive or ecologically appropriate on peat The economic rationale during replanting is especially strong where smallholders lose palm income before new trees bear fruit. Yet improved short-term cash flow must be distinguished from increased lifetime net present value. A field with promising annual-crop revenue can still generate a negative investment outcome if the intercrop damages young palm roots, competes for scarce water or nutrients, or delays future palm establishment. Conversely, temporary intercropping may support liquidity without materially increasing long-run returns, which could still be socially valuable for liquidity-constrained families. Research on Indonesian replanting shows that farmer willingness and capacity respond to income security, land documentation and support mechanisms, suggesting that enterprise design needs to be integrated with the replanting package rather than added after planting Crop-specific feasibility should consequently start with local agronomy rather than a nationally uniform commodity prescription. Pineapple, for example, has a different perishability and harvesting schedule from watermelon, and an ostensibly high-yielding maize cultivar may perform poorly where soil fertility or water supply is limited. Smallholder palm yield-gap studies show that basic palm management remains a major determinant of output, while nutrient surveys reveal imbalances that additional nutrient-demanding crops could aggravate if fertiliser programmes are poorly coordinated. The correct comparator is therefore not an unproductive monoculture managed below good practice, but a defensible baseline that includes appropriate palm management. Agronomic improvements alone can already raise palm yields and farm profitability, making the incremental value of an intercrop an empirical question.

TM Systems Shift from Sun-Demanding Crops to Understory Functionality

The second theme is the reconfiguration of land-use opportunity in mature plantations. Higher shade and more established palm root networks reduce the suitability of many food crops that perform well under more open canopies. Managed understorey vegetation may instead contribute ground protection, organic inputs, habitat for beneficial organisms and, where quality is sufficient, forage. The initial concept identifies grasses and legume covers such as Pueraria and Calopogonium species, but species-level suitability should not be extrapolated from their names alone. Shade response, biomass quality, potential competition, persistence, invasiveness and available management skills require local assessment, including precise botanical identification of planting material Oil-palm studies provide more direct support for the ecological value of maintaining some understorey than for the financial attractiveness of any individual forage mixture. Investigations in Indonesian smallholdings associate understorey vegetation with improvements in soil-health indicators, while butterfly surveys and biological-control research show that understory structure can affect communities involved in wider ecological functioning. Experimental mechanical weeding research likewise indicates that vegetation-management methods can influence ecosystem multifunctionality and profits under particular conditions. The key implication is not to maximise standing vegetation regardless of field operations; it is to define an appropriate, controlled mosaic that protects harvest circles, access paths and palm health while retaining ground-level ecological functions [43-45].

Biodiversity outcomes also depend on the surrounding landscape. Work on avian communities and natural pest suppression in small-scale oil palm indicates that shrub cover and proximity to continuous forest may matter, implying that a field-level planting change cannot be interpreted independently of forest edges or landscape composition. Research on landscape heterogeneity similarly identifies soil biota as a central element of restoration. Research tracking arthropods across oil palm replanting stages in Riau also found shifts in community composition despite no universal decline in total arthropod abundance, demonstrating the importance of taxon-specific indicators for some plantations, maintaining riparian buffers, native vegetation islands or ecological set-asides may yield more defensible biodiversity benefits than simply adding a market crop under the canopy. Those interventions may deliver few immediate sales but provide public ecological values; their financing should not be assumed to come entirely from smallholders [46,47].

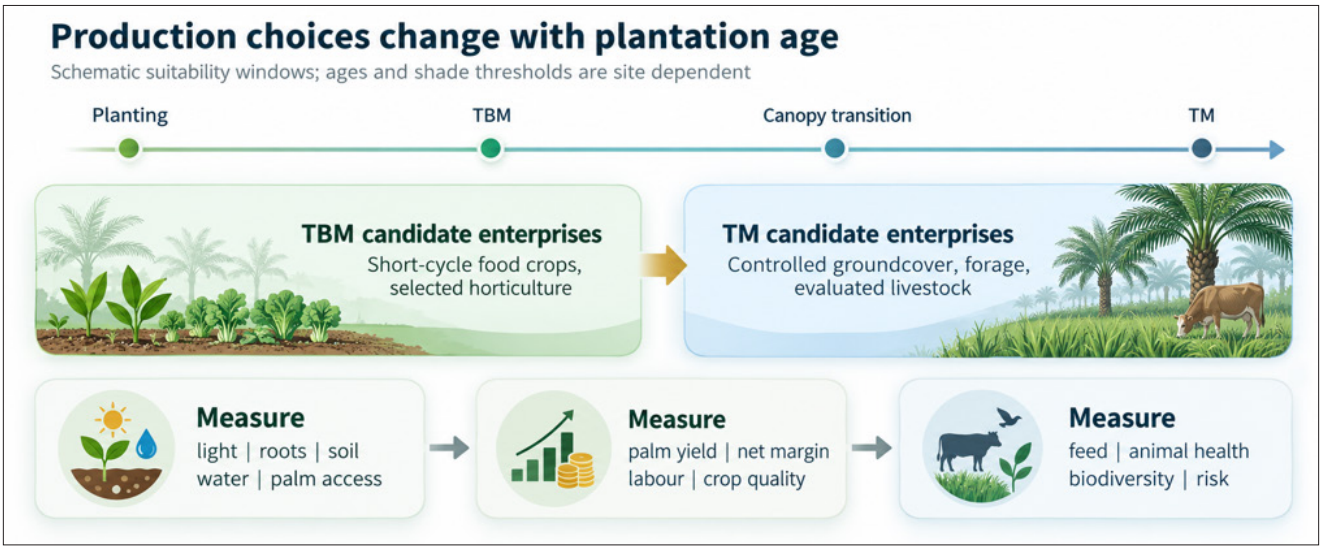


Figure 2: Changing Option Suitability and Monitoring Priorities Through the Oil Palm Plantation Lifecycle. Schematic; not an age-Based Agronomic Prescription.

Figure 2 presents the lifecycle-screening framework that follows from these findings and makes the changing requirements visible before any cmpanion enterprise is selected.

Figure 2 translates phase-specific evidence into a screening matrix. It places short-cycle annual or horticultural options predominantly within the TBM opportunity window and positions managed vegetation and selected livestock arrangements as conditional TM options. The matrix does not claim fixed planting dates, expected yields or universally applicable shade thresholds. It indicates which field measurements should precede a choice and why a design that succeeds in the first years after replanting may need to be phased out or transformed as palm canopy cover increases.

Small-Ruminant and Poultry Integration Offer Options but Not Automatic Synergies

The third theme concerns the difference between access to undergrowth and the productive capacity of livestock systems. Goats or sheep can potentially consume suitable forage, create an additional marketable product and provide manure for crop nutrient cycling. Nonetheless, animal performance is constrained by the seasonal quantity and digestibility of forage, supplementation, animal genotype, stocking density, heat load, parasite burden, drinking water and veterinary support. Crop–livestock reviews report benefits under successfully managed integration, but evidence from broad agricultural contexts does not identify an optimal flock size for Indonesian mature oil palm. A pilot should quantify dry-matter availability, nutrient composition, animal growth or reproduction, veterinary expenses and the opportunity cost of farmer labour before livestock expansion Ducks are conceptually different from grazing ruminants. Meat and laying-duck enterprises may produce food and cash income, but a reliable water supply, feed procurement, housing and biosecurity may matter more than the availability of understorey vegetation. Poultry cannot be presented as a free weed-control service unless the operational model has been evaluated for feeding behaviour, disease transmission and crop-protection effects. Likewise, livestock manure does not become a fertiliser saving automatically: collection, treatment, application rates, nutrient contents and potential runoff must be assessed to avoid pathogens and nutrient imbalances. The relevant circular-economy benefit is measured nutrient substitution and safe waste recovery rather than the mere presence of animals alongside palms the cattle debate illustrates why an evidence-graded approach is necessary. Some managed cattle–oil palm systems have reported profitable livestock sales or savings in weed management, whereas wider adoption is constrained by declining forage availability under ageing palms and unresolved palm-yield effects. identify weaker evidence for some purported yield gains and implementation challenges in smallholder free-grazing systems. Concerns regarding trunk or root damage, soil compaction, worker safety and disease-management compatibility warrant control measures and monitoring, but an assertion that cattle necessarily spread Ganoderma would exceed the evidence reviewed here. This manuscript consequently frames goats, sheep and ducks as pilot candidates from the initial concept presentation, while treating controlled cattle integration as an alternative requiring a separate suitability appraisal [55].

Ecological Gains Are Measurable, Conditional and Not Substitutes for Conservation

The fourth theme distinguishes ecological improvement within existing plantations from avoided damage outside them. The Sumatra tree-island experiment documented increased biodiversity and ecosystem functioning in enriched plots, showing that some forms of vegetation diversification can enhance production-landscape quality without reducing landscape-scale palm yield in the conditions studied. This is encouraging but not equivalent to demonstrating carbon neutrality, zero biodiversity loss or compensation for prior deforestation. Other work on set-asides argues that strategic retention or restoration of native habitats can enhance ecological value, while research on dry forest and grassy habitats cautions that narrowly defined forest-protection policies can also overlook other threatened ecosystems [48].

Understorey management requires attention to taxa that are rarely reflected in farm accounts. More structurally diverse vegetation can support insects, birds and soil organisms; however, biodiversity effects depend on disturbance intensity, landscape adjacency and species identity. A plantation could appear greener while still functioning poorly as habitat for forest-specialist organisms. Accordingly, monitoring should combine vegetation indicators with direct biodiversity measures where practicable, along with soil compaction, infiltration, erosion and nutrient balance. Using a single indicator such as crop yield, weed suppression or total leaf area would be an inadequate environmental assessment Carbon and climate claims demand additional restraint. Studies of agroforestry in other landscapes identify potentially positive carbon and sustainability outcomes, but initial land cover and the type of agroforestry system condition the comparison. A Brazilian oil-palm agroforestry study documented improvements in some soil fertility indicators without comparable improvements in all physical indicators, illustrating why soil health should not be reduced to a single score For Indonesian peatlands, drainage and rewetting strongly influence emissions and are not corrected simply by planting companion crops. Research on the climate-smartness of palm management and on climate-related risks further supports adaptation that accounts for water stress, changing weather and agronomic management. Integrating crops or livestock into ecologically vulnerable locations must not increase drainage, encroach upon natural forest or weaken existing protection and restoration obligations [49].

Labour, Planting Material and Markets Are Joint Implementation Bottlenecks

The fifth theme reinforces the original emphasis on three constraints: suitable labour, quality inputs and secure markets. Each crop has distinct agronomic and postharvest requirements, and livestock introduces daily husbandry obligations that can conflict with palm harvesting, fertilisation or household responsibilities. Training needs therefore go beyond simple planting instructions to include crop protection, harvest timing, product grading, bookkeeping and occupational safety. Evidence from integrated systems suggests that management capacity is a determinant of success, while palm management trials show that improvements may be feasible without raising overall labour requirements in every context; the labour effects of additional enterprises nevertheless need direct accounting Input quality is a second constraint but must be specified, not invoked rhetorically. The concept proposal notes the importance of superior planting material, yet certified seed or elite cultivars cannot compensate for inappropriate soil conditions, weak irrigation or a mismatched market. An input package should distinguish palm seedlings, companion-crop seed or propagules, forage planting material and livestock genetic stock, each with separate quality checks and biosecurity requirements. In plantations already exhibiting nutrient constraints, advisory services must integrate nutrient budgeting across commodities. In crop systems more broadly, diversification benefits are context-dependent, so local validation of varieties and technologies is crucial before assuming productivity gains The third bottleneck, access to demand, is decisive for highly

perishable produce. Selling a surplus requires an economically viable buyer, a harvest calendar, quality requirements, aggregation facilities, transport and credible payment arrangements. A sudden regional expansion of watermelon or banana output could depress farm-gate prices precisely when growers need cash; even a contract with an offtaker may not fully transfer this risk if rejection clauses, asymmetric grading or delayed payments are common. Hence the production plan should be reverse-engineered from demonstrable market demand, with tested buyer capacity and price scenarios. A plan limited to increasing tonnes produced may create excess supply rather than economic sustainability, particularly where smallholders have weak market bargaining positions [51].

Uneven Assets and Governance Create Unequal Opportunities

The sixth theme is distributional heterogeneity. Independent farmers, estate companies, village cooperatives and government plantation managers differ in land scale, record keeping, machinery, cash reserves, tenure security and willingness to accept seasonal losses. A corporate estate might centralise veterinary access and collection schedules but struggle with incentives for contracted household participation, while a smallholder may have flexible family labour but insufficient capital for irrigation or cooling infrastructure. Sustainability-certification experiences repeatedly show that farmer organisation and facilitation materially affect participation and costs. For multicrop partnerships, equivalent institutional questions concern who supplies inputs, who owns the produce, who may enter plantation land and who bears losses when harvests are rejected A multidimensional assessment of Indonesian oil palm smallholders illustrates that economic, ecological, social, institutional and technological dimensions require joint attention, rather than the assumption that additional income establishes sustainability on its own The evidence also argues against evaluating inclusion solely by participant counts. Certification studies report mixed financial effects, administrative costs and imperfect price premiums, revealing that more formal governance is not automatically more lucrative. Farmers may agree to intercrop because of pressing cash needs yet face hidden opportunity costs from unpaid household labour. Women and other household members may contribute extensively while lacking control over sales receipts. A defensible intervention must therefore monitor net returns and distribution of earnings alongside transparent land-use arrangements, grievance procedures and exit rights. These measures also reduce conflict over plantation access and clarify responsibility for crop damage and animal losses Evidence on oil palm agroforestry adoption in Jambi suggests that farmer attitudes and practical confidence can limit adoption even when the environmental rationale is appealing, so extension programmes should evaluate willingness and capabilities before inferring demand from consultations alone [53].

Table 1 consolidates the proposed companion enterprises into a phase-specific screening matrix that separates plausible benefits from decision-critical limitations. The options are not empirical rankings, and the table should be read alongside the site-screening criteria described above and not as an unconditional recommendation.

Table 1: Phase-Specific Option-Screening Matrix; Classifications Are Hypotheses for Local Validation, Not Proven Comparative Rankings

Option / setting	Potential benefit	Decision-critical limitation
Maize or watermelon (TBM)	Earlier seasonal revenue	Light, water, nutrients, labour and buyer access
Pineapple or banana (TBM)	Potential longer cropping window	Harvest duration, site suitability, logistics and plant protection
Legume/grass understory (TM)	Soil protection, potential forage	Shade response, access and net nutrient effects
Goats or sheep (TM; conditional)	Livestock revenue and biomass utilisation	Feed budget, fencing, animal health and palm protection
Ducks (TM; conditional)	Meat or egg enterprise	Purchased feed, housing, water and biosecurity
Cattle (site-specific option)	Possible forage and weed-management synergies	Stocking, low mature-stage forage, soil and safety effects

Table 1 compares candidate interventions without assigning numerical suitability scores unsupported by field trials. The 'conditional' label deliberately covers a wide range: a crop may be technically feasible but commercially unattractive, or an animal enterprise may have a market but lack adequate feed or disease control. Screening must be revisited as palms mature, as seasonal rainfall changes, or as market conditions evolve. This approach is more reproducible than a universal commodity recommendation because it identifies the minimum evidence a decision-maker must collect before committing land and capital.

Discussion and Analysis

The Central Synthesis: Sustainability Is a Constrained Optimisation Problem

Across the six themes, the clearest conclusion is that integrated production is a constrained optimisation problem rather than a single agricultural technology. A proposed commodity can deliver private profit but increase soil disturbance, improve soil cover but create no reliable buyer, or support biodiversity while limiting crop access for workers. The relevant objective is to increase total land- and household-level value subject to ecological thresholds, equitable allocation and acceptable downside exposure. The systematic treatment of agricultural trade-offs developed by is valuable here because it insists that productivity, social wellbeing and ecosystem outcomes be assessed together. General agricultural studies of ecosystem-service synergies strengthen this logic, while warning that spatial scale and stakeholder choice shape judgments about success A second lesson concerns evidence hierarchy. Cross-crop meta-analyses provide robust reasons to test diversification, whereas Indonesian oil-palm trials offer more immediate information on the management conditions under which outcomes can be expected. This hierarchy explains why positive aggregate effects

in rice systems or global agroforestry do not justify a blanket recommendation for watermelon beneath mature palms. The more convincing intervention is chosen from the intersection of site-specific crop physiology, operational access, expected market margin and verified ecological safeguards. Existing evidence on oil palm understorey, biodiversity enrichment and agronomic best practices allows formulation of this testable framework, but not a single best national model [50].

A Three-Gate Implementation Architecture

The first decision gate is biophysical and ecological suitability. Farmers and partners document plantation maturity, palm spacing, irradiance, soil fertility, drainage, erosion risk, protected vegetation, operational pathways and, for livestock, feed balance and water supply. Candidate enterprises that threaten young palm survival, intensify peat drainage, breach forest safeguards or introduce unmanageable animal-health risks should fail this gate even if forecast revenues appear promising. Ecological set-asides or tree islands may sometimes be the most valuable use of selected space rather than market cropping. The first gate therefore recognises both the agricultural opportunity cost and the public ecological function of land The second gate is enterprise and market viability. It requires an itemised annual and multi-year budget including planting inputs, household and hired labour valued at their opportunity costs, supplemental feed, veterinary care, postharvest losses, transport, financing charges and plausible palm-yield effects. Demand should be evidenced by buyers, indicative volumes, quality specifications and tested payment conditions rather than projections based solely on aggregate food consumption. Scenarios should include low prices, lower-than-expected yields, rejected produce and interrupted transport. A positive expected gross margin with high probability of severe household cash-flow loss is not an adequate definition of sustainability The third gate is institutional and social legitimacy. Land access must be lawful and documented, participation voluntary, responsibilities clear and benefits allocated transparently. Consent should also be renewed where contract terms change materially during canopy closure or partner turnover. Where land is owned by a firm but intercrops are managed by community members, written agreements should define seed financing, fertiliser placement, use of roads and irrigation, permitted working hours, crop ownership, insurance, dispute mechanisms and exit terms when palms shade out the intercrop. For livestock, veterinary accountability and procedures for animal movement and disease reporting must be explicit. The certification literature suggests that facilitation and farmer groups can lower participation barriers, but financing arrangements and governance performance should be monitored rather than presumed.

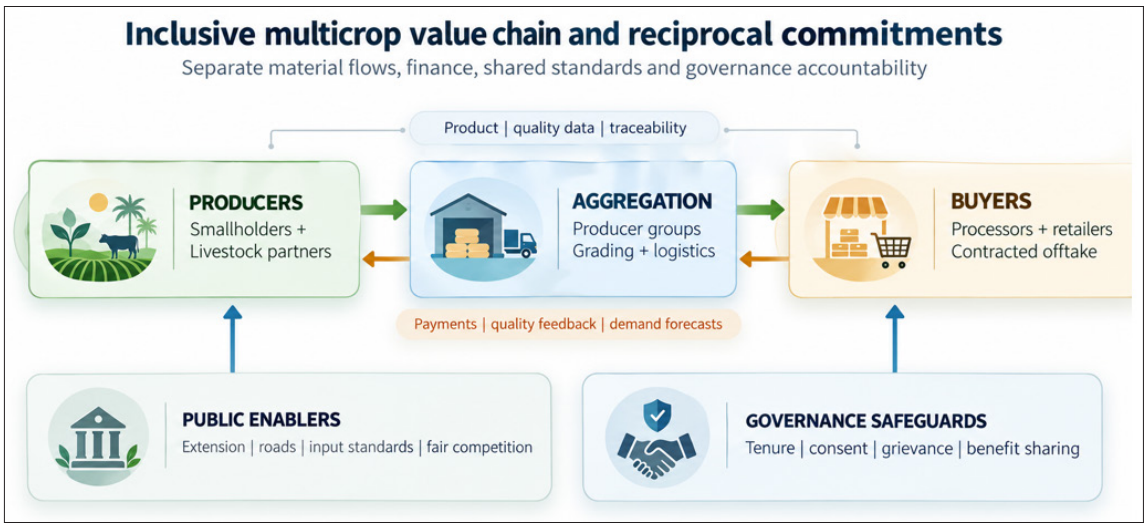


Figure 3: Inclusive Value-Chain and Institutional Coordination Architecture for Candidate Intercrop and Livestock Enterprises. Conceptual Representation

Figure 3 illustrates an inclusive transaction architecture involving growers or livestock partners, producer aggregation, processors or offtakers, and supportive public institutions. The arrows distinguish the physical movement of products from contractual commitments and information about demand. Such a model makes market coordination observable: delivery volumes, rejection rates, payment delays and farm-gate price dispersion become governance indicators rather than afterthoughts. Unlike a command-and-control assumption that government can directly set supply equal to demand, the framework positions public action as facilitation of infrastructure, standards, market transparency, finance and fair competition.

Figure 3 depicts the value-chain architecture required to convert additional production into reliable income and clearly allocated responsibilities

Economic evaluation: from gross output to risk-adjusted household benefit

A defensible economic analysis should compare at least three counterfactuals: business-as-usual palm management, improved palm agronomy without the companion enterprise, and improved palm agronomy with integration. This three-way comparison prevents attributing to intercropping gains that may be achievable from closing existing palm yield gaps. In TBM, the primary endpoint may be household cash-flow smoothing and discounted lifetime value; in TM, it may be additional net margin after preserving palm productivity and accounting for forage or livestock costs. Where land is jointly used, opportunity costs and transfer payments between estate owners and community partners need to be recorded separately to avoid double counting Simple accounting relationships can structure field monitoring without creating spurious precision. Additional annual net benefit can be defined as intercrop and livestock receipts minus enterprise

operating costs, added management labour, financing, postharvest losses and the value of any palm-output reduction; savings in herbicide or fertiliser use may be credited only if empirically demonstrated. A discounted cash-flow analysis should then model replanting years, the declining TBM growing window and eventual enterprise closure or transition. Sensitivity analysis should vary yields, quality-rejection rates, price spreads, animal mortality and labour availability. For welfare evaluation, median returns, cash-flow timing and the proportion of households incurring losses are as meaningful as the sample mean Decision analysis in horticultural diversification has shown why uncertain yields, prices and production constraints should be represented explicitly rather than compressed into a single deterministic expected margin For transparent comparison, the incremental annual net benefit of integration relative to an explicitly defined palm-only counterfactual can be expressed as Equation (1). All revenues and costs should be evaluated in constant currency per hectare or per participating household, with a consistent accounting boundary to prevent double counting across business partners.

$$\Delta NB_t = (R_{c,t} + R_{l,t} + S_t) - (C_{c,t} + C_{l,t} + C_{m,t} + L_t + D_{p,t})$$

(1) In Equation (1), ΔNB denotes incremental net benefit in year t; R is companion-crop (c) or livestock (l) revenue; S is demonstrably realised input-cost savings; C represents non-labour crop, livestock and management expenses; L is the opportunity cost of additional household or hired labour; and D captures any monetised palm-output loss relative to the counterfactual. Each component must be observed or modelled under transparent assumptions, and the sign of palm impacts must be retained even if the companion enterprise has positive sales. When an enterprise requires an initial investment and continues across multiple years, its incremental discounted value may be evaluated using Equation
(2). This is a proposed evaluation identity rather than an estimate of benefits from the literature review, and its inputs require location-specific pilot evidence. $NPV = -I_0 + \Sigma t = 1,\ldots,T\ [\Delta NB_t / (1 + r)^t]$ (2) In Equation (2), I_0 is the initial incremental investment, r is the real discount rate, and T is the evaluation horizon measured in years. The calculation must include the shortened TBM crop window, costs of terminating or adapting the companion enterprise and any delayed effects on palm productivity, with sensitivity analysis around prices, labour demand, animal survival and crop losses [47].

Evidence-Based Safeguards, Performance Indicators and Scale-Up Design

Environmental monitoring should begin before integration rather than after perceived damage. Baseline and follow-up data should include palm production, crop or animal output, soil fertility and compaction, erosion or infiltration, water quality where material, understorey structure and indicators of relevant biodiversity. Performance measures must match local risks: peatland hydrology in sensitive sites, food safety where manure is recovered, crop–livestock biosecurity for animal integration, and forest-edge integrity where landscape restoration is planned. Research on oil palm tree islands, peatland rewetting and ecosystem multifunctionality provides examples of multidimensional observation that can inform protocols, even though their exact instruments may not all be practical for village-scale pilots. Institutional measures are equally important. Trials should record the share of farmers with written agreements, days to payment, complaint resolution, women's access to earnings, buyer concentration, the proportion of production rejected or spoiled, and the distribution of returns among farmers, owners and intermediary actors. Trial designs should use matched comparison blocks or staggered introduction where feasible; for stronger causal inference, controlled or randomised comparison designs can be explored subject to ethical and operational constraints. A multi-season horizon is needed to capture rainfall variation, canopy closure and changes in farmer participation, while transparent reporting of failed pilots would reduce publication and demonstration bias.

Table 2 presents a multidimensional monitoring framework designed to prevent an isolated increase in secondary production from being mistaken for overall sustainability. Its indicator domains link palm performance and enterprise cash flow to environmental integrity, animal welfare and distributional accountability, while specifying a minimum interpretive safeguard for each domain.

Table 2: Proposed Multidimensional Monitoring Framework for Multicrop–Livestock Pilot Evaluation

Domain	Core indicator	Minimum interpretation safeguard
Palm enterprise	FFB yield, quality and stand health	Compare with improved palm-only management
Companion enterprise	Net margin, product losses, market price	Value family labour and capital; include negative scenarios
Environment	Soil indicators, water, biodiversity	Baseline, appropriate controls and protected-habitat safeguards
Livestock	Feed balance, mortality and welfare	Record supplementation, veterinary costs and disease events
Inclusion	Profit distribution, contracts, payments	Disaggregate by household and participant roles
Institutional performance	Buyer retention, disputes, rejected produce	Document contractual obligations and remedial action

Table 2: translates this argument into a measurement framework rather than an unsupported prediction of outcomes. It distinguishes outcomes attributable to the integrated enterprise from broader plantation performance and requires baselines in both categories. For example, a project should not be declared successful merely because its livestock sales increased if it simultaneously reduced palm yields or raised pressure on protected vegetation. Conversely, modest direct sales may be acceptable if additional household income is stable and verified soil or biodiversity benefits create a credible basis for co-financing.

Roadmap, Policy Coordination and Research Agenda

A practical programme can follow five linked stages, consistent with Figure 4: screen, design, pilot, evaluate and scale. Screening excludes ecologically unsuitable locations and identifies palm phase, land rights and community priorities; design establishes agronomic compatibility, buyer commitments, enterprise budgets and enforceable safeguards. Piloting then tests a limited number of options against improved palm-management controls, using consistent data collection and farmer training. Independent evaluation determines whether profitability, inclusion, palm performance, operational safety and environmental protection meet previously agreed thresholds before any wider scaling. A staged process recognises the uncertainty in agronomic translation and the different scale economies of

individual smallholders and estate-level services Public policy should enable information and coordination rather than guarantee profitable prices for every new enterprise. Relevant support may include reliable farm statistics, accessible extension, transparent input quality standards, rural roads, small-scale processing, collective marketing support, competition oversight and financing suited to replanting cash flows. Where society values biodiversity corridors or carbon benefits that farmers cannot monetise, appropriately governed co-financing may be justified, but it requires verification and protection against double counting. Intervention packages should also reflect climate and regional environmental differences; peatland sites, drought-prone areas and estates adjoining valuable habitat must not receive an identical template.

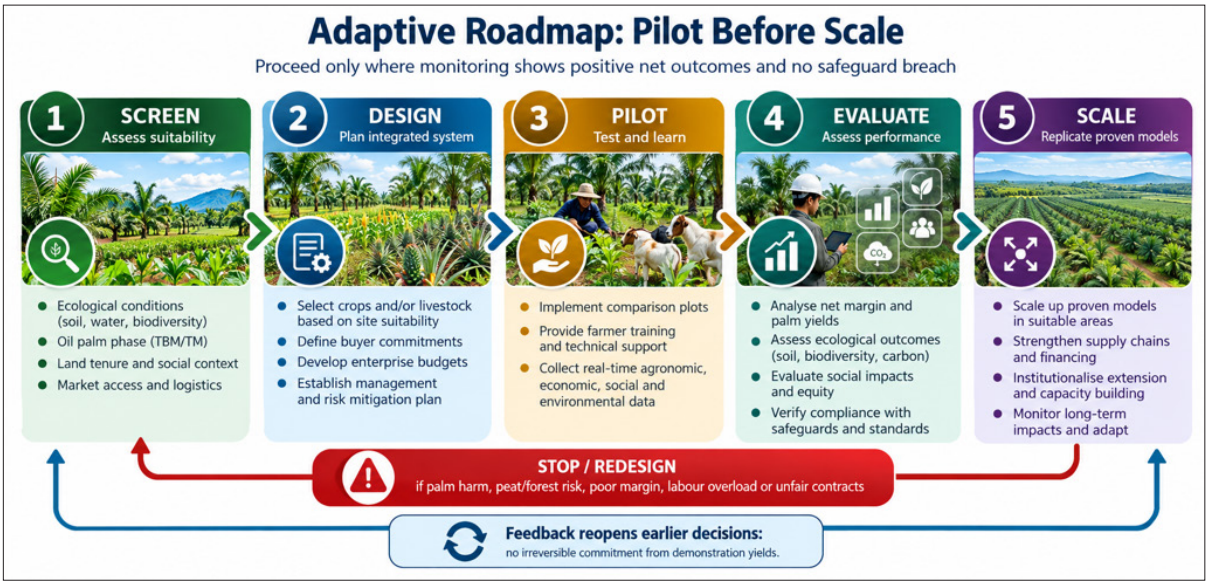


Figure 4: Adaptive Pilot-To-Scale Programmed with Explicit Stopping, Redesign and Evidence-Review Points. Proposed Implementation Framework

Figure 4 consolidates these stages into an adaptive roadmap with explicit stop-or-redesign triggers that precede scaling decisions Figure 4 summarises the phased implementation and feedback cycle. Its decision points are designed to prevent premature rollout based on high pilot yields, promotional photographs or temporary grant support. Evidence of adequate labour, reputable planting material and genuine buyer demand must be collected alongside ecological and distributive indicators. Failure to meet a threshold should trigger redesign, a narrower target crop, different livestock husbandry or termination, rather than automatic expansion of a poorly performing model. Two research priorities follow directly. First, comparative studies should test combinations of TBM crops and TM understorey treatments across multiple soil and rainfall settings, reporting component yields, water and nutrient competition, subsequent palm performance and fully costed margins over more than one season. Second, mixed-method studies should evaluate contracts, labour allocation, women's control of income, producer-group performance and buyer power alongside agronomic outcomes. Research into cattle integration, small-ruminant stocking density and duck husbandry should explicitly resolve feed, soil, hygiene and disease-management uncertainties rather than generalise from anecdotal examples. Nationally relevant evidence will come from replicated, context-rich comparisons rather than a single spectacular demonstration site [52-55].

Table 3: Implementation Risk Register and Suggested Responses, To Be Tailored to Pilot Conditions

Risk cluster	Illustrative exposure	Mitigation and decision trigger
Palm interference	Reduced young-palm growth or FFB output	Separate crop zones; stop when palm effects breach protocol
Soil and climate	Erosion, compaction, peat impacts	Site exclusion, hydrology and soil monitoring
Input failure	Poor seed or forage establishment	Certified provenance, varietal trials and replacement rules
Market shocks	Buyer failure, low price or spoilage	Diversify buyers; contractual delivery and payment provisions
Labour shortage	Seasonal conflict with palm harvesting	Calendar work demand; cost family labour and train workers
Livestock health	Disease, mortality or inadequate feed	Veterinary plan, stocking limits and disease response
Governance and equity	Disputed land access or benefit capture	Written consent, transparent accounts and grievance process

Table 3 summarises the implementation risk register and connects each exposure to a practical mitigation or decision trigger. The entries should be treated as locally adjustable pilot safeguards rather than thresholds that have already been validated across Indonesian plantation contexts.

Table 3 identifies leading risks and reasonable mitigation measures for the design and governance of multicrop programmes. These measures are propositions for field validation, not claims that they have already solved the documented problems. Incorporating clear abandonment triggers and transparent responsibility allocation makes the recommended programme more adaptive than a blanket commitment to diversified land use regardless of results.

Conclusion and Recommendations

The literature supports a qualified opportunity to enhance the multifunctionality of existing Indonesian oil palm landscapes, but the benefits of multicropping and livestock integration depend on plantation maturity, local ecology, managerial capability, household resources and credible markets. Immature plantations provide a temporary window for selected food and horticultural crops, whereas mature stands more plausibly support appropriately managed understorey vegetation and, where feasibility is demonstrated, compatible livestock enterprises. Neither option guarantees additional profit, biodiversity gains or improvements in palm yield. The value of the integrated approach lies in deliberately managing complementarity and trade-offs rather than maximising the number of commodities planted. Policy and business design should therefore move from production-led promotion towards market-informed, evidence-graded experimentation. The proposed three-gate framework requires biophysical suitability, risk-adjusted enterprise viability and legitimate governance to be demonstrated together. Implementation should begin with differentiated pilots, transparent agreements, strong ecological safeguards and measurements that include household wellbeing and the distribution of gains. Forest protection, peatland stewardship and sound palm agronomy remain independent obligations that diversification cannot replace. Longer-term replicated research and participatory monitoring are needed to determine which models can responsibly scale across Indonesia's diverse plantation landscapes.

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