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From Sea to Plantation: Prospects, Agronomic Evidence, Commercial Feasibility, and Industry-Led Adoption of Seaweed-Based Biostimulants in Indonesia's Oil Palm Sector

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Abstract

Indonesia's oil palm industry faces pressure to increase productivity while improving nutrient-use efficiency, climate resilience and environmental performance. At the same time, Indonesian seaweed aquaculture provides an established coastal bioresource base from which value-added crop inputs might be developed. This qualitative literature review critically examines whether seaweed-based plant biostimulants are scientifically credible and commercially viable complements to conventional oil palm fertilisation. Integrating 56 relevant journal publications from 2020-2026, the synthesis examines molecular mechanisms, cross-crop field responses, direct oil palm evidence, nutrient constraints, processing quality, life-cycle impacts and buyer-led commercialisation. Evidence supports biological plausibility and context-dependent effects in several crops; however, mature-palm evidence is insufficient to substantiate consistent increases in fresh fruit bunch yield or general fertiliser replacement claims. Widespread nutrient deficiencies in Indonesian smallholder fields make premature mineral-fertiliser reduction particularly risky. The article proposes a four-arm, multi-site randomised trial distinguishing add-on benefits from reduced-fertiliser effects, supplemented by nutrient monitoring, techno-economic analysis and environmental accounting. It further outlines a stage-gated partnership in which oil palm firms articulate demand and host trials, seaweed businesses develop standardised products, independent researchers evaluate outcomes and neutral facilitating partners coordinate inclusive precompetitive collaboration. A complement-first, substitution-only-after-proof approach offers a defensible pathway from blue-economy opportunity to evidence-based plantation procurement.

Keywords: Seaweed-Based Biostimulants, Oil Palm, Elaeis Guineensis, Nutrient-Use Efficiency, Fertiliser Complementarity, Kappaphycus Alvarezii, Plantation Field Trials, Techno-Economic Feasibility, Blue-Green Bioeconomy, Indonesia.

Introduction

The Strategic Problem of Crop Nutrition and Plantation Productivity

Indonesia's oil palm sector operates at the intersection of food and industrial oil demand, rural employment, soil stewardship and pressure to improve productivity on existing agricultural land. A credible productivity agenda therefore cannot rely only on expanding planted area or purchasing more inputs. It must improve the timing, placement and biological effectiveness of crop nutrition while preserving soil functioning and producers' financial resilience. Recent field evidence shows that agronomic practice explains material yield gaps in smallholder oil palm; fertiliser quantity, nutrient balance and broader field management cannot be treated as interchangeable constraints. This context creates a potentially attractive opening for crop biostimulants, but it also raises the burden of proof: a marketed biological product must demonstrate an incremental contribution over site-appropriate agronomy, rather than merely outperforming an inadequately fertilised control. Any proposal for seaweed products has to begin with that distinction [1-3]. The nutrient baseline is particularly consequential in perennial palms because deficient nutrition can constrain bunch development over extended periods. Surveys of Indonesian smallholder fields identify widespread nutrient deficiencies and considerable imbalance in nutrient supply, while a field-based analysis of potassium and magnesium uptake across contrasting sites in Sumatra demonstrates that fertiliser efficiency is conditioned by site characteristics and nutrient interactions. These findings undermine the simplistic proposition that a seaweed spray could eliminate a fixed percentage of nitrogen, phosphorus or potassium requirement across estates. They instead support an explicitly conditional hypothesis: under demonstrably sufficient nutrient supply, a correctly formulated extract might improve the plant's ability to use available resources or tolerate stress. Where a nutrient is limiting, that mineral deficit must be identified and corrected as part of the test design [2,4-6].

Independent soil observations strengthen the rationale for site-specific nutrient safeguards. Thompson-Morrison documented acidic, nutrient-poor soils and elevated concentrations of some trace elements in sampled Indonesian oil-palm production landscapes, thereby highlighting the importance of documenting soil chemistry before and after repeated input application [7].

These observations do not establish the composition or toxicity of a seaweed product, but they strengthen the case for baselines that cover both essential nutrients and contaminant exposure in pilot plots [2,7].

A Blue-Economy Opportunity Requiring an Agricultural Buyer

Indonesia also possesses an established seaweed aquaculture economy, with coastal households producing farmed macroalgae used in food ingredients, hydrocolloids and other processing chains. Work on Indonesian seaweed livelihoods documents both economic contributions and the importance of social distribution, including benefits experienced by women and households. Converting a portion of responsibly sourced marine biomass, processing residues or fit-for-purpose cultivated material into agricultural biostimulants could connect coastal enterprise development with a major domestic plantation market. Yet a prospective seaweed-to-palm industry is not automatically circular, inclusive or low carbon. Processing energy, chemical use, dewatering, packaging, transport and competition with higher-value existing uses may materially affect net benefits. The relevant proposition is not simply a national supply-demand match: it is a scientifically reliable product and an attractive supply contract that also withstands social and environmental scrutiny [8-11]. For this reason, the developmental roles of oil palm industry stakeholders, seaweed producers and neutral coordinating institutions are complementary but different. Estate operators and growers are potential paying customers, trial hosts and co-designers of commercially realistic success criteria. Seaweed processors and formulation firms bring product identity, manufacturing and quality-control capacity. Laboratories and independent researchers provide blinded assays, defensible comparators and external analysis. Public agencies clarify permissible product claims and traceability expectations. A convener can lower the transaction costs of building this system without endorsing a product or predetermining trial outcomes. This governance design is particularly relevant where suppliers advertise benefits observed in other crops but buyers need evidence of harvest-level performance in mature oil palm [12-15].

Aim, Scope and Contribution

This review asks whether seaweed-based biostimulants are a credible, commercially scalable complement to oil palm nutrition in Indonesia, and under what demanding conditions a measured fertiliser reduction could eventually be justified. It integrates plant physiology, marine biomass processing, plantation nutrient management, crop trial methodology, unit economics, life-cycle accounting and inclusive value-chain design. The object is not to calculate an average response for oil palm from unrelated crop studies, because field responses vary with product, cultivar, stress, soil, timing and management. Rather, the article organises available knowledge into evidence tiers, identifies hypotheses that industry can test prospectively and proposes minimum decision rules for pilot progression. Its original contribution is a linked agronomic-commercial framework that treats buyer validation and coastal supplier readiness as co-dependent requirements [16-18,12].

The paper adopts six guiding questions. They concern the biological mechanisms that might transfer to palms; the circumstances in which seaweed products could complement fertiliser; the status of mature-palm field evidence; suitable Indonesian biomass, formulation and safety pathways; economically meaningful buyer thresholds; and the governance of joint trials and inclusive scale-up. A deliberately important negative question sits behind all six: what observations would demonstrate that an apparent biostimulant benefit is too uncertain, too small or too costly to justify procurement? By giving negative results equal interpretive status with positive results, this study proposes an evidence pathway rather than a promotional narrative. Recommendations are consequently framed as conditional actions for industry, development partners and research institutions, not declarations of current commercial readiness [3,11,14,19].

Literature Review: Concepts and Theoretical Foundations

Biostimulants, Mineral Nutrients and Biological Fertilisers

Plant biostimulants are defined by the functional process they are intended to stimulate, such as nutrient-use efficiency, tolerance to abiotic stress or crop quality, rather than primarily by the direct delivery of nutrients. Mineral fertilisers, by contrast, contribute measurable amounts of essential elements to the nutrient budget. Microbial biofertilizers depend on specified organisms or their activity in nutrient acquisition and transformation. A seaweed extract may contain some minerals, polysaccharides and signalling-active constituents, and commercial products can blend multiple input categories, making label-based classification unreliable. The analytically sound approach is to distinguish the mechanism, quantify actual nutrient loading at the recommended field dose and evaluate the product against the claim it makes. A biostimulant can be valuable even when its own nitrogen or potassium contribution is agronomically negligible; conversely, a nutrient-rich extract cannot be assumed to confer an independent signalling benefit [19-22].

The distinction can be expressed through a nutrient balance: soil stocks and mineral inputs plus mineralisation and other nutrient additions must, over an appropriate period, cover crop removal and unavoidable losses without progressive degradation of productive soil capital. A biological input can modify uptake efficiency, root access or resilience, but it does not invalidate conservation of nutrient mass. For an oil palm plantation exporting nutrient-bearing fruit bunches, any proposed reduction in mineral fertiliser must therefore be reconciled against leaf tests, soil stocks, tissue removal and harvest outcomes. This is especially important for potassium-intensive fruit production and for magnesium interactions. A trial showing greener fronds or improved seedling height may justify mechanistic investigation, but cannot by itself establish that less fertiliser will maintain the nutrient balance of a mature, high-yielding estate [2,4-6,23].

Active Constituents and Stress Physiology

Brown, red and green macroalgae are not interchangeable raw materials. They vary in polysaccharide structure, minerals, phenolic compounds and secondary metabolites, while cultivation conditions and postharvest handling introduce additional chemical variability. Brown-seaweed products based on Ascophyllum nodosum have a substantial international literature, but this should not be confused with direct evidence for Indonesian farmed red seaweeds such as Kappaphycus or Gracilaria. The relevant Indonesian innovation challenge is to identify standardised raw-material specifications and extraction conditions that preserve reproducible functional activity. Reviews of Ascophyllum and Kappaphycus biostimulants describe plausible biological activity, yet the transferability of any one branded extract depends on its chemistry, dose and crop-specific response. Product identity is therefore an experimental variable rather than background information [13,24-26]. Several proposed response pathways have

reasonable mechanistic foundations: changed root initiation or root architecture, improved osmotic adjustment, antioxidant responses, stomatal regulation and signalling pathways associated with stress tolerance. Molecular studies of maize grown under soil-moisture stress show transcriptional changes following Kappaphycus-derived treatments, while experiments with tomato seedlings link some seaweed responses to abscisic acid-associated signalling during water deficit. Work in cucumber cotyledons and pea flowering likewise demonstrates that effects may involve growth regulation rather than nutrient supply alone. These studies establish biological plausibility, not equivalence across crop species. An oil palm is a long-lived monocot with distinctive canopy, root distribution and reproductive sinks; the specific physiological route linking extract application to bunch yield requires separate validation [27-30].

Evidence from abiotic-stress research broadens the list of testable hypotheses without removing uncertainty. Reviews discuss how biostimulant formulations might modulate oxidative stress, drought responses or growth under unfavourable environments. Experiments in sorghum and maize investigate seaweed applications under water or salinity stress, whereas work in sweet cherry indicates potential leaf-water-status and photosynthetic responses in a woody perennial. A seaweed extract mitigated drought-related performance losses in an experimental sugarcane setting, a crop whose monocot biology is useful but still not a substitute for oil palm field observations. For plantations, a sufficiently constrained hypothesis could be improved establishment under transplant stress or a smaller yield penalty in defined moisture-stressed blocks. Broad claims of universal drought resilience are scientifically weaker because ambient stress, dose and formulation can all change response direction [31-37]. Extraction technology is another active causal element. Water-based, alkaline, acidic, thermal and emerging extraction approaches can select different chemical fractions and alter bioactivity or contaminant concentrations. Studies of brown macroalgal processing and chemical profiling of Laminaria and Ulva extracts show that the route used to make an extract can determine both composition and developmental effects. Literature focused on manufacturing also cautions against equating a laboratory concentration with an agronomically optimal dose. A commercially relevant protocol should record species, provenance, moisture, extraction solvent, temperature, concentration, preservatives and application method, rather than cite only a broad category such as seaweed extract. In the absence of batch traceability, a successful small experiment cannot be confidently reproduced by a buyer receiving later production lots [15,20,26,38,39].

Comparative formulation studies make clear why biological effects should not be generalized from a seaweed species name. Vaghela chemically characterized minimally processed homogenates of Kappaphycus alvarezii and Sargassum wightii and investigated tomato responses under contrasting moisture conditions, illustrating the need to connect extract composition with realistic application concentration [40]. For an oil-palm candidate, this means documenting active-constituent fingerprints and process reproducibility before attributing a field response to a broadly defined raw material [13,40].

Evidence Transfer, Perennial Crop Nutrition and Adoption Theory

The strongest general support for crop-level usefulness is found in field-trial syntheses rather than only molecular demonstrations. A meta-analysis of field biostimulant experiments reports heterogeneous yield effects; a more focused analysis of Chinese seaweed-based inputs likewise reports mean gains across crops, and a recent meta-analysis identifies formulation, extraction and application strategy as important moderators. Such pooled findings can inform a prior belief that agronomic activity is plausible, but they do not identify an oil palm treatment effect. The denominators of the underlying comparisons also matter: a product added to low-input management answers a different question from a product added to carefully optimised plantation fertilisation. Industry should therefore ask for oil-palm-specific response distributions, not an imported average percentage from annual crops [14,17,18]. A complementary theoretical lens is the economics of adoption under uncertain information. Plantation managers invest in inputs only when expected net benefits exceed acquisition, spraying, training, monitoring and operational risk costs. Biostimulants can be difficult to evaluate because their reported effects are contingent on weather and baseline nutrition; the resulting information asymmetry favours attractive demonstrations that do not isolate the product effect. Controlled on-farm experimentation can reduce that asymmetry by turning technical claims into auditable marginal comparisons. Techno-economic analyses of macroalgal production show that upstream processing choices influence viability, while life-cycle reviews warn that the least expensive product on a delivered-cost basis is not necessarily the one with the lowest environmental burden. Economic, agronomic and environmental thresholds therefore have to be jointly considered [11,12,14,41].

The Indonesia-specific adoption model also requires attention to heterogeneity between large estates, plasma arrangements and independent smallholders. Estates may have laboratory infrastructure, mechanised application options and procurement departments, while smallholders experience different credit constraints, fertiliser access, labour costs and risk tolerance. Recent Indonesian oil-palm research demonstrates the power of better agronomy, the diversity of nutrient imbalances and the relationship between understory, fertilisation practice and soil condition. These factors generate an opportunity and a rival explanation simultaneously: a product could produce a genuine complementary benefit, but apparently superior plots may simply have received more attention, more water or better basic management. Any technology claim should therefore be evaluated against a fully specified agronomic baseline and evaluated for segment-specific commercial feasibility [1,3,4,42]. Finally, a credible biostimulant value chain must be consistent with blue-economy sustainability rather than defined by the marine origin of the feedstock. Studies of Indonesian aquaculture describe livelihood and well-being outcomes, but equitable returns depend on contractual structure, quality grading and who controls processing margins. Global analyses point to seaweed farming as a potential contributor to land-use objectives under particular substitution scenarios, while life-cycle studies reveal diverse environmental outcomes across processing routes and end uses. For an oil palm input, it is essential to compare the incremental environmental burden of extraction and transport with any independently demonstrated reduction in fertiliser manufacture, field emissions or yield-adjusted land use. Avoided emissions should be credited only to measurable effects under a clear counterfactual, not to the seaweed label itself [8-11,41].

Methodology: Qualitative Literature Review

Review Design and Transparent Source Selection

This study uses a qualitative literature review, specifically

a critical and interpretive narrative synthesis, rather than a systematic literature review or meta-analysis. The objective is conceptual integration across agronomy, plant physiology, seaweed aquaculture, environmental assessment and industrial procurement. The source base emphasises peer-reviewed articles published from 2020 through October 2026, including studies of seaweed extracts in annual and perennial crops, field-based research on Indonesian oil-palm nutrition, and work on marine biomass supply chains. Relevant searches were organised around combinations of seaweed, macroalgae, biostimulant, Kappaphycus, Gracilaria, oil palm, nutrient-use efficiency, stress tolerance, life-cycle assessment and techno-economics. Sources were assessed for direct relevance and credible research design; there is no assertion of exhaustive database retrieval or a reproducible PRISMA screening flow [2,13,14,16,]. Source interpretation proceeds through three transferability tiers. Tier A contains studies directly involving oil palm, its nutrient budgets, yields or plantation conditions; Tier B contains relevant perennial crops, monocots or field settings from which a mechanistic hypothesis might reasonably be adapted; and Tier C contains controlled environments, annual crops, molecular assays and broader systematic syntheses that establish possibilities rather than field-ready prescriptions. A study may be strong evidence for one claim and weak evidence for another. For example, changes in gene expression in oil palm can support a mechanism hypothesis without validating a fertilisation reduction, while a wheat field trial can inform experimental methods without specifying a plantation dose. This claim-specific appraisal is more informative for procurement decisions than a single generic quality label attached to entire papers [3,34,43,44].

Thematic Coding and Safeguards Against Overclaiming

Interpretive reading organised findings into six connected themes: biological mechanisms, oil-palm nutrient constraints, applicability of crop trials, Indonesian marine supply readiness, commercial and environmental viability, and partnership governance. Within each theme, attention was given to effect direction, treatment comparators, scale of measurement, duration, environmental moderators and unexplained alternative mechanisms. Contradictory or null findings, uncertainty about product chemistry and incomplete yield endpoints were treated as analytically important rather than excluded as inconvenient. The review does not calculate a synthetic pooled effect for oil palm because comparable mature-palm trial datasets were not identified in the referenced corpus. Likewise, illustrative trial arms and procurement thresholds proposed below are hypotheses for prospective testing, not results already observed [14,17-19].

Methodological quality is discussed relative to the decision at hand. A supplier wishing to claim early rooting benefits must provide nursery observations with robust controls and objective growth measurements. A supplier wishing to claim better mature-palm yield must measure fresh fruit bunch production and oil-related outcomes across sufficiently long harvest windows. A supplier wishing to claim fertiliser displacement must additionally show maintained crop nutrition and no unacceptable soil nutrient depletion under reduced elemental input. The study also screens literature for the strength of environmental and commercial assumptions, particularly whether extraction energy, logistics and product standardisation are included. This sequential evidentiary logic permits useful early-stage research without allowing a mechanistic observation to be sold as a proven economic return [5,11,12,33].

Boundaries and Interpretation of Uncertainty

Several limitations require explicit acknowledgment. Publication bias may favor positive crop responses; proprietary formulations limit repeatability; physiological experiments often use growth stages or application doses that do not match estates; and yearly weather variability can mask or exaggerate treatment effects. Literature published late in the 2020-2026 window may not yet have independent replication. Indonesian seaweed production statistics and product registration rules can also change, so policy implementation must be checked against the rules effective when procurement begins. No confidential institutional or proprietary industry data have been used in this manuscript, and the proposed partnership is a recommended model rather than a description of an agreed institutional arrangement. These boundaries make the conclusions more conditional, but also more actionable: the next necessary step is a structured, independently verifiable comparison in oil palm [3,15,41,43].

Results: Thematic Findings

Theme I-Biological Plausibility is Substantial, but Performance is Conditional

The combined literature suggests that seaweed extracts can modify several physiological processes associated with plant performance, although neither all sources nor all preparations operate in the same way. Reviews describe responses in root growth, osmotic status, antioxidant processes and signalling pathways; experiments using sugarcane, maize, tomato and other crops provide particular mechanisms under specified conditions. These observations create a defensible reason to study seaweed products as plant biostimulants. They do not establish that application will increase harvestable oil-palm fruit, especially when there is no drought, the crop is nutritionally adequate or a formulation delivers compounds at a nonresponsive developmental stage. The result is a conditional plausibility finding: biological activity is credible, but the economically decisive phenotype remains species-, site-, product- and management-specific [16,21,31,45-48]. Studies outside oil palm also suggest that a product may improve development under both favourable and nitrogen-constrained conditions. Research on Kappaphycus-derived formulations in cucumber and pea reports distinct developmental responses, including growth and flowering, while experimental work in rice seedlings and common bean suggests possible roles in early establishment. A cassava study tested potassium-rich material manufactured from Gracilaria salicornia in a semi-arid environment, illustrating a potentially relevant red-seaweed processing direction. Yet these results should not be pooled casually: some preparations have substantial intrinsic mineral content, and a positive response can reflect nutrient supply, biostimulation, improved water status or interactions between them. A properly designed palm experiment must chemically characterise the dose and isolate these explanations rather than assigning all gains to a single presumed hormone-like mechanism [29,30,39,49,50].

The most directly relevant seaweed-oil-palm peer-reviewed evidence identified in this review is a 2022 study by Kresnawaty and colleagues, which examined seaweed-extract plant-growth regulation in relation to expression of genes associated with oil production and metabolites in oil palm. Its existence matters: oil palm is not wholly absent from the seaweed biostimulant literature. Nevertheless, its endpoints should not be converted into a claim of improved commercial harvests. Molecular or metabolic signals cannot establish durable fresh fruit bunch response, oil extraction rate, fertiliser savings, cost effectiveness or plantation-wide

repeatability. The gap between biochemical evidence and estate purchasing criteria is consequently large. An important immediate research opportunity is to connect careful mechanistic assays in oil palm with blinded product comparisons and harvest-scale agronomic measures in ordinary management settings [14,19,43]. A recent meta-analysis focused on cereals exposed to salinity provides a useful example of endpoint discipline. Nuruzzaman reported improvements in shoot and root biomass with aqueous seaweed extracts under salinity stress, while explicitly noting that corresponding evidence for cereal grain-yield responses remains limited [51]. This distinction is instructive for oil palm: a demonstrated stress-related physiological or growth response may justify a focused research hypothesis, but fresh fruit bunch and oil-yield effects must be measured independently rather than inferred from vegetative improvement [43,51].

Field syntheses reinforce why the response question must remain open. The 2024 Chinese meta-analysis finds positive average crop-yield responses to seaweed fertilisers, while a 2026 meta-analysis indicates that yield effects depend significantly on application and extraction characteristics. An earlier meta-analysis of field biostimulants shows that trial context changes effectiveness. Those patterns justify experimentation, but a cross-crop mean should not appear in a palm business case as a forecast without local testing. Effect sizes observed in wheat under irrigation treatments, cherry, sugarcane or maize arise from different growth cycles, stress regimes and product application frequencies. The central empirical finding is therefore heterogeneity: a probability of response exists, but no scientifically supportable single percentage describes expected mature-palm yield uplift from Indonesian seaweed extracts [14,17,18,33,34,44].

Theme II-Nutrient Sufficiency Limits Defensible Fertiliser Substitution

Indonesian oil palm evidence places nutrient adequacy ahead of biostimulant substitution. A major survey of smallholder sites documented extensive shortages of essential nutrients, and companion work identified imbalanced fertiliser application. Differences in potassium and magnesium acquisition at Sumatran sites further show why a standardised reduction in fertiliser is unsafe across diverse blocks. Improved crop response following biostimulant addition could be valuable under an optimised nutrient baseline, but it cannot compensate for a persistent elemental mass deficit at the plantation system boundary. These findings lead to a hierarchy of claims. The lowest-risk claim is improved establishment or stress management when fertiliser practice is held constant. The intermediate claim is increased nutrient-use efficiency supported by tissue and yield outcomes. The highest-burden claim is reduced fertiliser without yield or soil-capital loss over time [2,4-6]. A limited number of field experiments in other crops have explored seaweed products in reduced-nitrogen regimes. The engineered Ascophyllum product evaluated in managed grass under lowered nitrogen inputs provides an example of the appropriate comparison logic, while work on Kappaphycus-derived products in pea considers nitrogen-limited conditions. However, those experiments do not demonstrate that a palm plantation can safely reduce a given percentage of its nitrogen, potassium or other fertilisers. Fertiliser displacement is a counterfactual question: would the identical block, climate, crop and management perform equally well over time with a lower mineral dose plus seaweed extract, compared with the best justified standard fertiliser schedule? Answering it requires factorial or equivalent randomised controls, not comparisons between treated and untreated areas that have otherwise different nutrient histories [3,30,44,52].

The time dimension compounds this constraint. Nutrient depletion can be concealed temporarily by soil reserves or internal redistribution in palms. A short trial may maintain fruit bunch output while drawing down exchangeable potassium or altering leaf nutrient concentrations, creating later costs not visible in its initial budget. Conversely, bunch yield may respond slowly to improved canopy or reproductive development, so an early null result need not establish a permanent absence of benefit. For this reason, trials should set distinct short-term endpoints for nursery vigour or leaf physiology and longer-term endpoints for harvest performance, soil nutrient budgets and economic value. Reduced-fertiliser experiments should require a pre-specified nutrient-safety stop rule and independent laboratory checks. The resulting patience may seem commercially inconvenient but is necessary to protect both plantations and suppliers from misleading early inferences [1,5,6,42]. The essential distinction between biological plausibility and plantation proof is visualised in Figure 1. A material extracted from seaweed first has to be chemically identified and applied consistently, after which a physiological response must be demonstrated in the intended palm system. Only a subsequent, independent test of harvest and nutrient outcomes can establish whether that response has commercial relevance. The diagram makes these evidentiary stages explicit to guide study design and the language used in supplier claims [16,19,43].

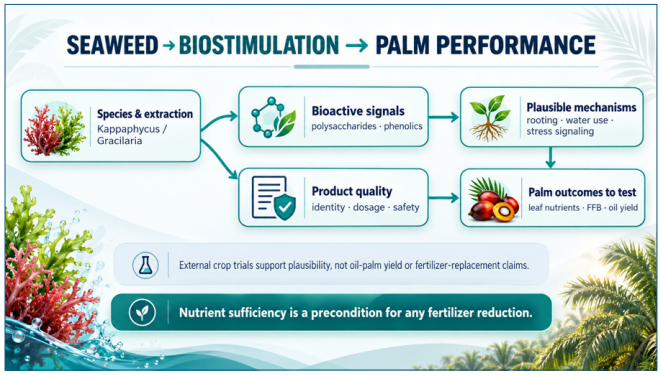


Figure 1: Mechanistic Pathway and the Evidence Gap Between Seaweed-Product Chemistry and Measurable Oil Palm Outcomes. Author Synthesis of the Cited Literature.

Figure 1 separates the proposed causal chain into raw-material and processing decisions, signalling-active chemistry and quality assurance, plausible physiological mechanisms, and outcomes that an estate can measure. The arrows are deliberately hypotheses rather than proven causal effects in mature oil palm. A scientifically useful claim needs evidence at the appropriate link: extraction characterisation establishes what enters the field; plant assays establish a response; and harvest measurements establish agronomic usefulness. This architecture helps prevent a common category error, in which one observed molecular response is taken as proof of higher oil yield or a fertiliser-saving entitlement. It also indicates why batches and formulation details are essential for experimental replication and eventual supply contracts [13,19,27,43].

Theme III-Indonesia has a Plausible Marine Feedstock, not a Ready-Made Product Specification

A seaweed-derived crop input could be developed from Indonesian

red seaweeds already embedded in commercial aquaculture, especially cultivated Kappaphycus and selected Gracilaria strains. The existence of production, drying, collection and export channels offers an initial industrial advantage: businesses already understand biomass handling and coastal logistics. Indonesian studies describe community-level livelihood contributions and the distribution of benefits within households. Nevertheless, industrial agriculture has different requirements from a hydrocolloid buyer. It needs predictable biological activity per litre, stable formulation, workable concentration, reasonable shelf life, reproducible cost and field application compatibility. The existence of a seaweed farm therefore establishes feedstock opportunity, not biostimulant efficacy. Candidate species and grades should be selected on chemical characterisation and performance, not only local abundance or a compelling circular-economy story [8,9,13,49]. Species and processing are key sources of uncertainty. Red macroalgal polysaccharides, brown-seaweed alginates and green-seaweed derivatives differ, and extraction can yield mixtures with quite different biological activity. Work reviewing seaweed-derived polysaccharides describes a wide chemistry-to-function landscape; trials with Galaxaura, Kappaphycus and Ascophyllum demonstrate that results observed with one biomass cannot identify the active dose of another.

Industrial processing also changes viscosity, stability and compatibility with sprayers. Suppliers seeking oil palm customers should consequently present at least species authentication, dry-matter content, pH, soluble solids, relevant mineral profiles, extraction protocol, stability testing and a batch fingerprint. Such an agreed minimum specification would support both experimental interpretability and later product acceptance. Its exact thresholds should be product- and regulator-specific rather than invented in advance [24,26,28,38-40,53]. Contaminant risk is not theoretical simply because macroalgae grow in marine environments. Research comparing standards for iodine and several potentially toxic elements in macroalgae shows that origin, use and regulatory context matter. A crop product requires a distinct risk assessment from edible seaweed, but testing for relevant metals, microbiological hazards and undesirable residues remains prudent, particularly where repeated application could accumulate substances in soil or introduce occupational exposure. For possible coastal by-products, salinity and sodium loading also deserve screening so that processing impurities are not transferred into plantation soils. A commercial quality-assurance system should identify laboratories, detection limits, lot-release criteria, recall capability and obligations when specifications fail. Product safety and consistency are gates before broad agronomic experimentation, not matters to address only after a positive growth result [7,11,15,20,54].

Theme IV-Economics, Environment and Commercial Evidence must be Assessed Together

Commercial viability requires an estate manager to compare the delivered, applied cost of the biostimulant against the expected marginal increase in saleable fresh fruit bunches or another monetizable benefit. The numerator includes extraction, packaging, warehousing, transport, finance, labor, machinery, water and monitoring; the denominator should incorporate the actual area treated and application frequency. If a trial introduces more management visits or a more precise foliar program, those costs and benefits must not be omitted. A product that works only at uneconomically high doses is a scientific lead rather than a procurement opportunity. Conversely, a small but reproducible benefit may be attractive if dosing can be integrated into existing operations with low incremental labour. The necessary evidence therefore extends beyond treatment significance to margin, sensitivity, operational feasibility and downside risk [3,11,12,14]. A particularly useful distinction is between gross response and net benefit. In a simplified commercial comparison, incremental annual benefit equals the change in saleable output value plus genuinely avoided fertiliser and other costs, less the complete additional cost of the seaweed intervention. The trial should report uncertainty around each term, including harvest price volatility and labour requirements. Avoided fertiliser cost must be booked only if a reduction has passed agronomic safeguards; it cannot be counted twice as both a theoretical efficiency gain and a physical saving. Break-even values for fresh fruit bunch response can be derived for each estate from its input price and realised harvest economics, without inserting a universal uplift assumption. For smallholders, financing availability and cash-flow timing are additional obstacles even when a product could be profitable on average [1,3,12,17].

A transparent marginal-profit calculation is necessary because incremental FFB revenue and actual input savings can move in opposite directions. Equation (1) defines annual net benefit per hectare relative to the estate-specific reference, with all additional operating costs counted rather than excluded from the comparison.

$$\Delta\pi = \Delta R_{FFB} + S_{fert} - C_{product} - C_{application} - C_{monitoring} \quad (1)$$

Here $\Delta\pi$ denotes the difference in annual net return per hectare; the revenue term measures incremental fresh fruit bunch sales, and the savings term measures fertiliser expenditure demonstrably avoided. The three cost terms measure additional product, application and monitoring expenditure; hypothetical fertiliser savings must not be credited if a lower mineral-input rate fails nutrient-stock or yield safeguards [5,12]. Environmental analysis points to a similar necessity for counterfactual accounting. Reviews of seaweed life cycles show sensitivity to cultivation methods, drying, processing energy and transport. Recent life-cycle work on seaweed-derived biostimulant production highlights potential manufacturing and packaging hotspots that may offset part of an assumed environmental benefit. Accordingly, low-carbon branding should depend on a product-specific life-cycle inventory and transparent system boundaries. Potential credits such as lower mineral fertiliser manufacture, changes in field nitrous oxide emissions or higher output from existing land cannot be assumed without evidence that the relevant effect actually occurred. Indonesian oil palm already has measured fertiliser-related greenhouse-gas and ecosystem flux challenges, so the strongest environmental argument is an experimentally demonstrated improvement in emissions intensity or input efficiency, not an unqualified assertion that a marine-derived input is inherently sustainable [10,11,41,55,56].

Supply-chain social performance is the remaining component of readiness. Coastal growers may face quality discounts, price swings, working-capital limits and unequal access to processing profits. Indonesian research shows that seaweed income contributes to livelihood outcomes and household well-being, including gendered effects. In an oil palm biostimulant chain, inclusive procurement could be operationalised through transparent grades, predictable payment schedules, producer-group participation and documented labour and environmental safeguards. These features may improve supplier resilience but also create costs to budget transparently. The proposed blue-

green economy connection is compelling precisely because its social claims are testable. It should be judged by changes in producer returns, contract reliability and distribution of value, not simply by the number of coastal communities appearing in a project narrative [8-10,12]. A market for tested biostimulants also requires a shared architecture for demand, supply and credible knowledge, summarised in Figure 2. The schematic distinguishes the provision of biomass and formulations from the evaluation of crop outcomes, while recognising that neither stream is commercially meaningful without purchasing criteria from oil palm growers. Independent research and transparent governance act as connecting infrastructure. This is particularly relevant where developmental outcomes, such as coastal producer inclusion, must coexist with competitive procurement decisions [8,9,12].

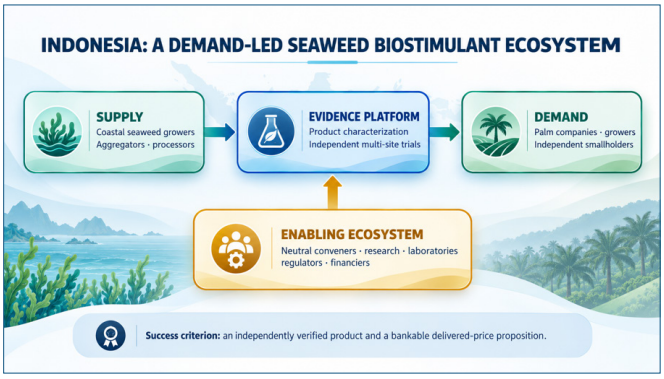


Figure 2: Proposed Indonesian Seaweed-to-Oil-Palm Innovation Ecosystem, Actor Responsibilities and Independent Evidence Loop. Author Synthesis.

Figure 2 presents demand, supply and independent validation as interconnected functions rather than a linear promotional partnership. Growers and estates define the management problem and the maximum tolerable operational cost, suppliers control product specification, laboratories establish composition and safety, and research teams compare treatments using agreed protocols. Neutral coordinating institutions can facilitate precompetitive standards and inclusive coastal sourcing, while industry associations and buyer consortia can mobilise prospective trial hosts and articulate market requirements without prejudging the value of any brand. Feedback from field trials should change product specifications and procurement decisions. The figure is a governance proposal; it does not imply that any participating institution has already endorsed a formulation, committed to purchase or agreed to the experimental design [3,8,12,41].

Discussion and Analysis

Answering the Six Research Questions

The response to the first research question is qualified optimism about mechanism and pronounced uncertainty about mature-palm impact. Seaweed-derived compounds can plausibly affect rooting, signalling, osmotic responses and plant stress physiology; multiple studies outside oil palm support these pathways. However, individual extracts vary chemically and agriculturally, and the palm-specific study provides a biological starting point rather than evidence of a repeatable plantation yield effect. The practical implication is to prioritise formulations with an interpretable chemical identity and a clearly stated use case. A supplier offering a nursery establishment product should be judged on survival, rooting, establishment time and costs. One offering a mature-palm yield product needs harvested fresh fruit bunch data and fruit or oil-quality endpoints. Neither should use a mechanistic finding as a substitute for the performance claim buyers are being asked to finance [14,16,27,39,43]. The second question concerns when biostimulants might complement fertilisation. The clearest near-term proposition is additive or resilience-oriented use under an otherwise sound nutrient program. Candidate circumstances include transplant establishment, episodic moisture stress, stressed soil environments or blocks where nutrient availability is constrained despite a defensible fertiliser plan. Such targeting offers a more rigorous and potentially more profitable hypothesis than broadcasting a product over all palms. It also facilitates learning about moderators rather than obscuring them in a plantation-wide average. A prospective reduced-fertiliser claim should be considered separately, after the product has shown value at full site-specific fertility and after a risk assessment of the limiting nutrient. In low-fertility blocks, the appropriate first intervention may be better N, P, K, Mg or B management, not an additional biological input [2,4,33,34,42].

The third question asks how compelling direct field evidence currently is. For Indonesia's mature oil palms, the available peer-reviewed seaweed-extract evidence assembled here is not sufficient to state that the technology consistently increases fresh fruit bunch or oil yield, maintains soil fertility under reduced fertiliser, or delivers a positive commercial return. The existing oil palm biochemical study is notable but cannot bear those conclusions. Studies of Indonesian crop management provide a useful comparison by showing that properly measured agronomic changes can generate substantial gains; they also show why a trial must compare a seaweed intervention with a strong business-as-usual baseline. The defensible research conclusion is not that seaweed products fail, but that the crucial plantation outcome remains unproven. That uncertainty should directly determine the depth and duration of industry pilots [1,3,5,43]. For the fourth question, Indonesia has a plausible route from cultivated macroalgae to standardised agricultural products, especially if supplier development builds on existing red-seaweed infrastructure. Commercial readiness depends on identity, activity, stability, safety and traceability rather than biomass volume alone. The literature supports laboratory screening of different seaweed species and extraction routes, but it does not currently identify a universally superior Indonesian species or formulation for mature oil palm. Product candidates should therefore be subjected to a common performance specification and compared at economically realistic doses. Procurement contracts should specify batch conformity, independent laboratory rights and remedies for off-specification supply. This transforms the innovation problem from an open-ended promise about seaweed into a competition among characterised and testable formulations [8,13,20,49,54].

The fifth question concerns the purchasing threshold. A plantation customer is not buying plant physiology as such; it is buying a credible improvement in net return, risk management, input efficiency or compliance at an acceptable delivered price. A provisional business case can model several response scenarios, but those scenarios must be labelled assumptions until backed by field data. Financial viability should be tested for differing labour regimes, estate scale, rainy-season access, product concentration and seaweed feedstock price. If a proposed fertiliser saving is included, any resulting risk of depleted nutrient stocks or future yield loss must also be valued. Seaweed processing must then pass a related upstream test: production scale and quality systems should lower cost without destroying biological activity or relying on unstable residues. Only where both margins are credible does

a durable buyer-supplier market begin to emerge [3,11,12,41]. The sixth question addresses institutional design. An effective cross-sector research partnership should start with buyer-defined research questions, not an inventory of products awaiting demonstration. Industry partners can nominate representative estates and smallholder networks, assign agronomy leads, agree to independent access to production data and provide the operational cost information needed for evaluation. Seaweed producers and processors can compete to meet a transparent chemistry and price specification, while researchers design experiments without commercial control over reporting. Neutral conveners can reduce coordination costs, safeguard inclusion objectives and help translate independently verified results into shared standards. Industry associations or buyer consortia can represent demand priorities while avoiding conflicts associated with exclusive commercial promotion. This division of responsibilities encourages learning even when some candidate products fail the trial [8,9,12,14].

A Field-Trial Architecture that can Generate a Purchasing Decision

The proposed evidence program begins with analytical product characterisation and small controlled screens before advancing to mature field trials. Gate-zero laboratory work would measure identity, physical and chemical properties, relevant elements and contaminants, concentration and stability, and compatibility with application systems. Nursery testing would then compare untreated and treated palms within a common fertility and irrigation regime, with randomised assignment, objective measurements and batch records. Only formulations that show an interpretable signal at a plausible delivered cost should progress to estates. This sequence prevents a costly multi-location study of a product that cannot be manufactured reliably. It also enables selection among multiple suppliers on common criteria. Screening should be run at realistic doses, because unrealistic concentrations can produce laboratory effects that disappear when translated into an affordable field program [12,27,29,49,54]. At the mature-palm stage, a minimum informative experiment uses factorial treatment contrasts rather than a simple demonstration strip. Treatment A is the locally justified full fertiliser standard without seaweed input; treatment B is the same standard plus a specified seaweed product. Treatment C applies a pre-approved modestly reduced fertiliser regime without seaweed, and treatment D combines that reduced regime with the product. This design separately estimates the incremental add-on benefit, the consequence of reducing fertiliser, and whether biostimulant application offsets any reduction penalty. A reduction example of roughly 10-15% is an exploratory design parameter, not a general fertiliser recommendation, and should never be applied when baseline nutrient status or crop risk makes it inappropriate. More rates may be necessary where chemistry or dosage-response evidence suggests nonlinear effects [2,5,14,52].

Figure 3 presents the proposed treatment matrix for separating an additive response from the consequences of nutrient reduction. Its four arms encode the counterfactual questions that an estate purchasing team needs to resolve before accepting either an enhancement claim or a substitution claim. The arrangement does not assume that a reduced fertiliser treatment will be safe at any particular site. Rather, it makes any reduction conditional on nutrient diagnosis, research approval and pre-specified monitoring rules [2,5,52].

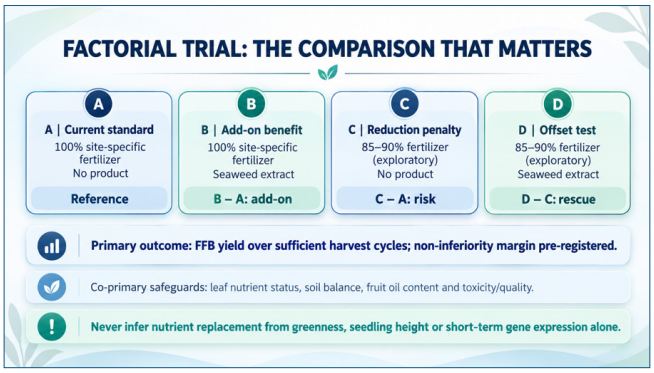


Figure 3: Proposed Four-Arm Factorial Pilot for Separating Additive Biostimulation from Nutrient-Reduction Effects; Fertilizer Percentages are Illustrative, not Agronomic Advice.

Figure 3 shows why the most common on-farm comparison, product versus no product under poorly described conditions, is insufficient. The B-minus-A contrast asks whether the extract adds value to adequate nutrition. C-minus-A measures the risk associated with changing mineral input alone. D-minus-C determines whether the product improves the reduced-input regime, while the interaction between reduction status and product application examines whether their effects are independent. A further important comparison is D versus A: did the full reduced-fertiliser package achieve an acceptable harvest and nutrient outcome compared with current practice? Each interpretation requires randomisation, replication and blinding where feasible. If only a two-arm pilot is financially possible, industry should begin with A versus B and postpone any fertiliser-displacement claim rather than infer substitution from the wrong design [2,14,18,52]. The factorial interpretation can be made explicit by an interaction contrast, which compares the biostimulant response at reduced fertiliser with its response at the standard nutrient regime. Equation (2) captures that contrast in FFB yield, and its uncertainty must be estimated using the trial's randomisation and repeated-harvest structure.

$$I_Y = (Y_D - Y_C) - (Y_B - Y_A) \quad (2)$$

In Equation (2), the four yield variables denote adjusted fresh fruit bunch production in treatment arms A through D, while the left-hand side represents the difference-in-differences interaction. A positive interaction would indicate a larger biostimulant response under fertiliser reduction, but it does not establish that treatment D is economically attractive, nutritionally safe, or non-inferior to treatment A [5,14,52].

Site selection must represent the market and the biological uncertainties. A useful consortium would stratify trial blocks by age of palms, soil and topography, rainfall or seasonal water deficit, planting material, prior fertiliser history, and high versus marginal nutrient status. Treatments should be randomised within appropriately homogeneous blocks, with border palms or buffer zones minimising cross-treatment spillover. Harvest measurers should ideally be unaware of treatment assignment, and raw records should cover bunch number, bunch weight, area, date, fertiliser dose, weather, leaf diagnosis and relevant maintenance operations. Multi-season monitoring is essential because reproductive and yield responses lag treatment. The protocol should include a power calculation based on plausible detectable effects and site-level

variance, rather than announcing an arbitrary number of palms as universally sufficient [1,3,5,42].

The main decision endpoint should reflect commercial use. For mature stands, this would normally include fresh fruit bunch yield per hectare over an extended, pre-agreed harvest window, with oil content or extraction-rate evidence where measurement is feasible. Secondary endpoints could include nutrient-use-efficiency indicators, leaf and soil nutrient status, rooting or canopy physiology, drought-related performance, fruit quality and the frequency of application-related damage. Researchers must separate biochemical and physiological secondary endpoints from the primary buying decision. A trial may legitimately conclude that an extract increases a leaf-level antioxidant marker but fails to deliver a material harvest or financial benefit; such a result is informative and should not be reclassified as commercial success. Reports should provide effect sizes and intervals, not only whether a conventional significance threshold was crossed [5,14,34,43]. For fertiliser reduction, the program additionally needs a pre-registered non-inferiority framework. The allowable yield-loss margin cannot be chosen after results appear; industry and independent agronomists should define a margin reflecting economic risk, statistical precision and the time horizon. Non-inferiority on fresh fruit bunch yield is necessary but not sufficient if leaf potassium, magnesium or soil reserves decline, or if application increases unwanted residues. Statistical analysis should account for repeated harvests and hierarchical site variation, and sensitivity analyses should test whether a few unusual drought blocks drive an overall result. A reduction claim may need several years of observation and a longer follow-up for soil nutrient stocks. The appropriate decision can therefore be to continue measurement even after an encouraging first season rather than accelerate commercial purchasing [2,5,6,42].

Commercial results should be collected prospectively, not reconstructed after a yield response emerges. For every treatment, the study should record supplier price, delivered volume, application labour, machinery, transport, storage loss, number of sprays, monitoring expense, and any actual fertiliser expenditure avoided. Profit comparisons should reflect observed output values, not only agronomic percentages, with scenario analyses for product price and commodity-price volatility. A parallel life-cycle inventory should track cultivation, biomass drying, extraction energy, chemical inputs, packaging, distribution and field operations. Any environmental savings attributable to reduced fertiliser should use the actual randomised contrast and clearly defined boundaries. These paired analyses would let procurement committees rank products by evidence of net value and environmental consequence rather than by supplier narratives or isolated yield headlines [11,12,41,55].

Stage-gated collaboration and commercialisation

Evidence gates can convert a complicated research undertaking into manageable industry decisions. Gate 0 verifies product identity, manufacturing reproducibility, contaminant control and initial delivered-price plausibility. Gate 1 tests a mechanistically coherent response first in nurseries and subsequently in replicated mature-palm fields. Gate 2 decides whether incremental financial benefits, agronomic safeguards and environmental indicators are acceptable under the pre-registered comparator. Gate 3 concerns the supply chain: capacity, contracts, quality control, traceability, farmer inclusion and long-term monitoring. Failure at any gate should trigger redesign, a narrower use claim or discontinuation without stigma. A product might pass as a nursery establishment aid yet fail as a mature-palm fertiliser-saving input. Such differentiated authorisation is more credible than all-or-nothing endorsement and can stimulate honest market segmentation [3,12,15,54]. The move from agronomic screening to procurement can be organised as staged decisions rather than a single broad authorisation, as illustrated in Figure 4. The sequence gives industry an operational way to spend modestly on uncertain formulations and concentrate larger investments on candidates that clear quality, efficacy and cost tests. It also allows a supplier to revise a product or narrow its intended application without misrepresenting an unsuccessful mature-palm result. Finally, it separates legitimate development facilitation from product endorsement by insisting on independent evidence at each gate [12,14,41].

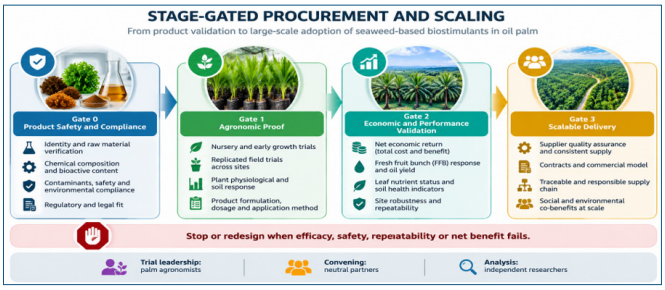


Figure 4: Proposed Stage-Gated Evidence, Procurement and Supplier-Readiness Pathway for an Industry-Led Pilot. Author Synthesis.

Figure 4 depicts four decision points and makes the right to stop an essential governance feature. It also separates the role of the independent evidence team from the commercial ambitions of suppliers and users. At each gate, a short public-facing technical summary could record the hypothesis, comparator, product batch, sample size, observed endpoint, uncertainty and reason for progression or cessation. Proprietary process details can remain commercially protected if the product can still be independently identified and measured. In this arrangement, independent conveners can promote transparent coordination and social safeguards, while the industry retains responsibility for defining purchase value and researchers retain authority over inference. Shared lessons from unsuccessful products may be especially useful for reducing duplication across estates and suppliers [9,11,14,19]. A demand-led procurement compact could give industry participants an efficient method for expressing interest without committing to premature large-volume contracts. Participants would first agree to a common request for information requiring species identification, chemical specifications, preliminary safety data, application cost and independent field results where available. Suppliers passing documentary screening could then enter standardised laboratory and nursery evaluation, followed by multicenter estate trials hosted on comparable terms. Any later purchasing process should be competitive and explicitly conditional on performance thresholds. This arrangement can avoid two failures: supplier-funded trials whose datasets cannot be audited and fragmented company demonstrations that cannot be combined because each uses a different comparator. Precompetitive evidence standards benefit responsible suppliers by making robust performance visible, even if proprietary product formulas differ [12,13,17,41].

Financing should follow evidence maturity. Development funding has a reasonable role in convening, independent testing, quality infrastructure, farmer inclusion and knowledge that multiple firms can use. It should not subsidise indefinite commercial application

in the absence of demonstrated customer value. Suppliers can contribute product, manufacturing information and a portion of trial costs, while industry provides blocks, records and operational support. A jointly governed data-access agreement can preserve confidentiality of estate-level information while permitting independent aggregated estimates. Conflicts of interest must be declared, especially where an evaluator has consulting or commercial ties to a product. A successful pilot may then lead to offtake, licensing or further technology development, but those are commercial choices after-and not substitutes for-the evidence [8,9,12,14]. Equity must also be built into the transaction architecture rather than added as a closing aspiration. The seaweed component should identify coastal producer groups, quality-grading practices, labour arrangements, gender participation and payment terms. The oil-palm demand side should determine whether smallholders can access the product at an economically realistic package size and receive truthful advice about its use alongside essential fertilisers. Digital batch traceability can support both sides if it is simple enough for growers and processors to maintain. Excluding independent smallholders or coastal microenterprises could produce a technically successful estate input with weak development additionality. Conversely, requiring every supplier to meet burdensome certification before any technical support may entrench incumbents. A phased system that provides training before demanding compliance is more consistent with inclusive market formation [8-11].

Wider Policy and Research Implications

For researchers, the immediate priority is comparative dose-response work on characterised Indonesia-relevant species, followed by replicated harvest-scale studies. For estate agronomists, the priority is identifying candidate blocks where a biological intervention answers a real management problem without jeopardising nutrient sufficiency. For product developers, the priority is stable manufacture, independent assays and price competitiveness at the proposed field dose. For public institutions, the priority is clarity about allowable product classifications, claims, testing and quality standards. These tasks need not be completed in strict sequence: joint protocol design can inform supplier engineering while laboratory work proceeds. However, a positive political or commercial narrative cannot accelerate biological validation. A future research portfolio could also compare seaweed extracts with alternative biostimulants and basic agronomic improvements to establish relative value [3,15,19,42]. The strongest long-term opportunity is not merely to market a marine-derived spray, but to build a reproducible innovation system connecting coastal bioresources with tropical perennial crop performance. Its broader value may emerge through local extraction capability, analytical laboratories, improved product standardisation, farmer-oriented agronomy and environmental information that can be reused for other crops. Nevertheless, oil palm should remain the focal validation setting rather than a convenient prospective sales story. A mature industry partnership will publish null findings, distinguish research funding from purchasing decisions and openly identify conditions under which a product should not be used. The practical result is a conditional commercialisation pathway: proceed when consistent agronomic benefits, credible net economic returns and auditable safeguards coincide, and decline or redesign when they do not [8,12,18,41].

Conclusion and Comprehensive Recommendations

Substantive Synthesis

Seaweed-based biostimulants represent a plausible innovation opportunity for Indonesian oil palm because they can contain biologically active constituents, because international crop research documents context-dependent physiological and yield responses, and because Indonesia already has important seaweed aquaculture capacity. None of these premises, separately or collectively, proves a mature-palm yield benefit or fertiliser replacement rate. The decisive limitation is the gap between chemical or molecular activity and sustained field evidence across representative oil-palm environments. That gap is especially consequential given widespread nutrient deficiencies and the long time horizon over which a perennial plantation absorbs nutritional mistakes. The appropriate opening proposition to industry is therefore complement-first: protect evidence-based mineral nutrition, test a characterised extract for additional benefit and investigate substitution only through a risk-controlled comparison. The scientific, commercial and development opportunities are conditional on one another. Reliable manufacturing enables meaningful agronomic comparison; meaningful comparison supports a real buyer willingness to pay; and an actual commercial margin creates a market that can strengthen coastal livelihoods. A product that fails quality or safety controls should not proceed simply because it uses local biomass. A product that shows laboratory activity but no economic field effect may merit further research but not routine procurement. A product that delivers yield but increases environmental burdens or concentrates value in a narrow processing segment requires redesign of the business model. The highest-value innovation may ultimately be a limited use case-such as nursery establishment or recovery after specific stress-rather than broad replacement of mineral fertiliser.

Prioritised Recommendations and Research Agenda

The first practical recommendation is to establish an industry-led, independently evaluated pilot consortium with an explicit demand specification, transparent supplier entry criteria and a common protocol. It should characterise candidate red- and brown-seaweed products, undertake safety and stability screening, test nursery hypotheses and then compare full-fertiliser and reduced-fertiliser treatments in stratified mature-palm blocks where scientifically defensible. Second, consortium participants should pre-register success and stop criteria, protect leaf and soil nutrient status, maintain long-enough harvest records and publish interpretable findings, including null results. Third, buyer economics and life-cycle inventory should be measured alongside crop outcomes. These practices will turn a potentially contentious fertiliser-replacement narrative into a rigorous decision about whether, where and for whom a seaweed biostimulant creates value. The second strategic recommendation is for industry representatives, research institutions and neutral conveners to make learning, standards and inclusion the shared public goods of the initiative. Suppliers should retain incentives to innovate, while coastal growers should benefit from fair grading, reliable payments and environmental safeguards. Oil-palm smallholders need protection against exaggerated yield or fertiliser-saving claims, practical application guidance and access to results expressed as costs and benefits per hectare. Regulators and laboratories should be engaged early on product identity, allowable claims and quality control. This agenda provides a defensible route from an attractive blue-green economy hypothesis to measured industrial opportunity. The final decision to scale should rest on independent plantation evidence and durable net benefits, not on the presumed sustainability of seaweed origin or on cross-crop averages.

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