



Biofertilizers as a Conceptual Framework for Futuristic Yield Gap Analysis and Sustainable Productivity of Oil Palm in Malaysia

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Abstract

Oil palm (*Elaeis guineensis*) is one of the most economically significant crops in Malaysia, yet yield stagnation, soil degradation, and environmental constraints increasingly challenge long-term productivity. Conventional yield gap analysis typically focuses on agronomic inputs, management practices, and climatic variability, but emerging evidence suggests that biological soil processes and microbial functionality play critical roles in determining crop performance. The objective of this narrative review is to integrate microbial ecology, soil fertility dynamics, sustainability assessment, and resource circularity into a unified model of productivity potential and limitation. Drawing on advances in microbial ecology, circular bioeconomy practices, environmental sustainability assessment, and agronomic performance studies, the framework integrates soil microbiome function, nutrient cycling, stress resilience, and resource recovery pathways into yield gap evaluation. Biofertilizers are examined not merely as input substitutes for chemical fertilizers but as systemic regulators of soil-plant interactions and ecosystem functioning. Evidence from diverse cropping systems demonstrates that biofertilizers enhance nutrient use efficiency, crop yield, soil health, and resilience to environmental stressors while supporting circular waste valorization and carbon mitigation strategies. This paper synthesizes interdisciplinary research to establish a multi-layered conceptual model linking microbial processes, soil fertility dynamics, environmental sustainability, and productivity optimization. The proposed framework redefines yield gaps as biologically mediated productivity differentials shaped by ecological, technological, and socio-economic factors. The study concludes that integrating biofertilizer science into yield gap assessment provides a forward-looking pathway for sustainable intensification of oil palm production in Malaysia while aligning with climate resilience and circular bioeconomy principles.

Keywords: Oil Palm; Biofertilizer; Yield Gap Analysis; Sustainable Productivity; Malaysia

Introduction

Oil palm (*Elaeis guineensis*) cultivation represents a cornerstone of Malaysia's agricultural economy and global vegetable oil supply. However, the sector increasingly faces productivity constraints linked to soil degradation, nutrient imbalance, environmental stress, and sustainability pressures. Traditional yield gap analysis focuses primarily on genetic potential, agronomic management, and resource inputs. While these factors remain important, growing scientific evidence indicates that soil biological processes and microbial functionality play fundamental roles in determining crop productivity and resilience. Biofertilizers, which enhance plant growth through biological nutrient mobilization and microbial interaction, therefore offer an expanded perspective for understanding productivity

variation across landscapes [1,2]. The global transition toward sustainable agriculture has intensified interest in biological soil management as an alternative to chemically intensive fertilization systems. Biofertilizers contribute to nutrient cycling, plant growth promotion, and soil structural improvement through microbial activity and ecological interactions. Field evidence demonstrates that biofertilizer application enhances crop yield and soil health under diverse agroecological conditions [3,4]. Importantly, these effects extend beyond nutrient supply to include stress tolerance, disease suppression, and microbial community restructuring [5]. Such multifunctionality suggests that biofertilizers influence productivity through systemic ecological pathways rather than isolated agronomic mechanisms. Recent research further

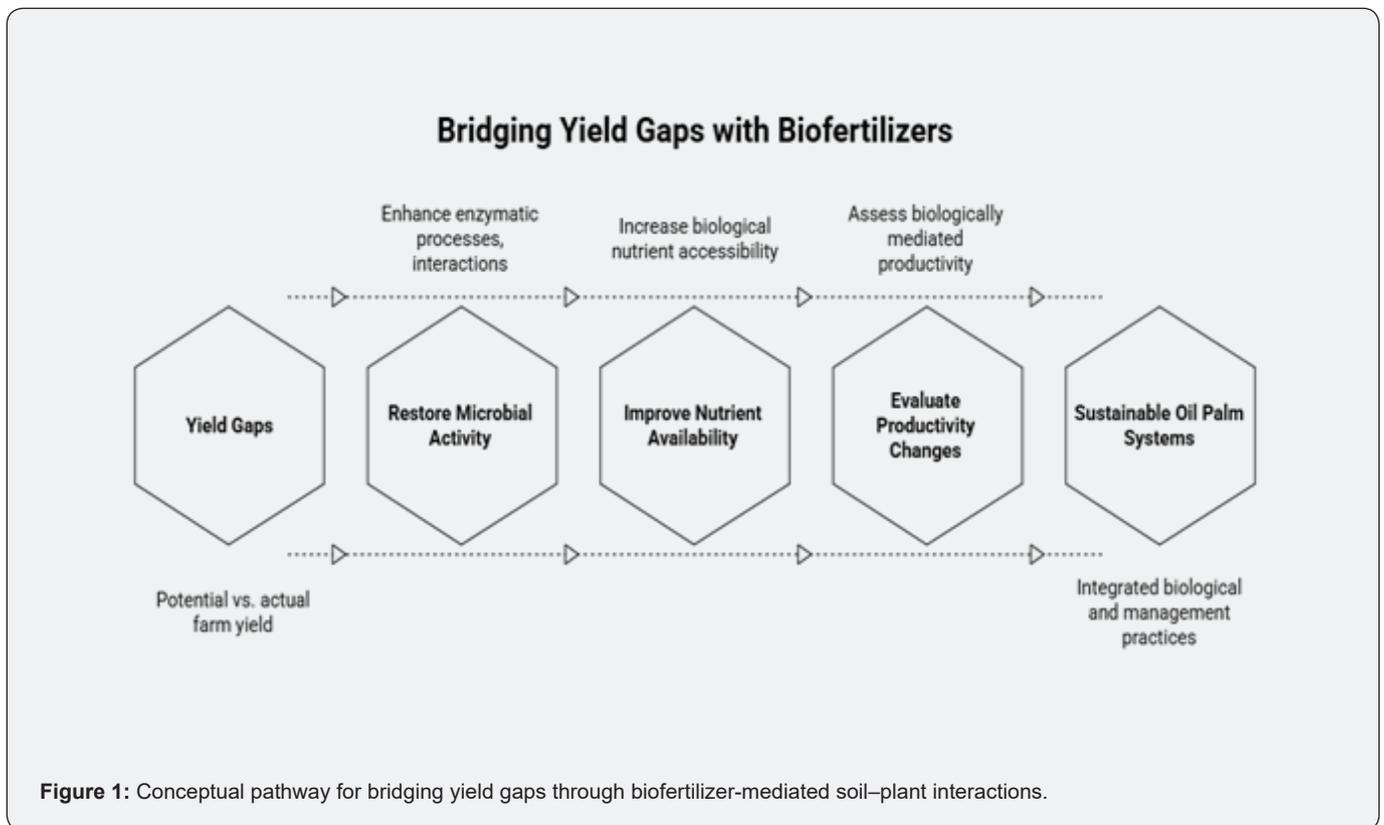
highlights the role of microbial community dynamics in regulating soil fertility and plant performance.

Interactions between introduced biofertilizer organisms and native soil microbiota determine functional stability, nutrient transformation efficiency, and long-term ecosystem integration [6]. Plant growth-promoting rhizobacteria, nitrogen-fixing bacteria, and symbiotic fungi contribute to nutrient availability and stress adaptation across multiple crop systems (Sofyan et al., 2025; Srivastava et al., 2025). These findings suggest that biological processes form a critical yet under-represented dimension of productivity analysis. In parallel, biofertilizer research increasingly intersects with circular bioeconomy and environmental sustainability agendas. Waste streams from agriculture, industry, and municipalities are now converted into biofertilizer products, creating nutrient recycling pathways and reducing environmental burdens [7] (Martín-Sanz-Garrido et al., 2025). Microalgae-based systems simultaneously remove pollutants, capture carbon, and generate biomass suitable for agricultural use [8,9]. These developments indicate that biofertilizers operate within broader ecological and resource management systems. Despite these advances, yield gap analysis in oil palm systems rarely incorporates biological soil processes as central determinants of productivity. This paper therefore proposes biofertilizers as a conceptual framework for reinterpreting yield gaps in oil palm cultivation. The objective of this narrative review is to integrate microbial ecology, soil fertility dynamics, sustainability assessment, and resource circularity into

a unified model of productivity potential and limitation.

Conceptualizing Yield Gaps in Oil Palm Systems

Figure 1 illustrates a conceptual framework showing how biofertilizers contribute to narrowing agricultural yield gaps by progressively enhancing biological and ecological processes within oil palm production systems. Beginning with the discrepancy between potential and actual farm yield, biofertilizer application is positioned as a catalyst for restoring microbial activity, improving nutrient availability, and strengthening biologically mediated productivity. These sequential processes ultimately lead to measurable productivity improvements and the establishment of more sustainable oil palm systems supported by integrated biological and management practices. The framework emphasizes that yield gap reduction is not solely an agronomic adjustment but a biologically driven transformation governed by soil microbiome function, nutrient cycling, and ecosystem resilience. Yield gaps traditionally represent the difference between potential yield and actual farm yield. Classical frameworks attribute this difference to agronomic management, nutrient availability, water limitation, and pest pressure. However, these approaches often treat soil as a passive medium rather than a biologically active system. Emerging ecological research suggests that soil microbial communities regulate nutrient transformation, organic matter turnover, and plant stress response, thereby directly influencing realized productivity [2]. In oil palm plantations, long-term monoculture and intensive fertilization frequently reduce microbial diversity and disrupt nutrient cycling.



Altered soil biological structure may therefore create hidden yield constraints not captured in conventional models. Studies show that biofertilizer application can restore microbial activity and improve nutrient availability through enhanced enzymatic processes and cooperative microbial interactions (Wang et al., 2026) [1]. These findings imply that biological soil degradation contributes to yield gaps. A biologically informed yield gap model must therefore distinguish between physical resource limitations and ecological functionality limitations. Productivity loss may occur even when nutrients are present but not biologically available due to microbial imbalance. Conversely, microbial enhancement may increase nutrient efficiency without increasing input levels. This perspective reframes yield gaps as outcomes of ecosystem function rather than solely management intensity. Biofertilizers provide a practical tool for investigating these dynamics because they directly modify soil microbial composition and function. Their effects on nutrient cycling, plant growth regulation, and stress tolerance allow evaluation of biologically mediated productivity changes. Hence, biofertilizers can serve both as interventions and diagnostic indicators of ecological productivity constraints. Integrating biological processes into yield gap analysis expands the conceptual boundaries of productivity research and aligns

with sustainability-oriented agricultural models.

Biofertilizers as Biological Productivity Regulators

Figure 2 presents a structured conceptual model illustrating how biofertilizer-mediated microbial processes interact with soil physicochemical properties, nutrient cycling pathways, plant physiological performance, and broader environmental sustainability indicators to influence oil palm productivity. It highlights the interconnected layers of biological activation, improved nutrient use efficiency, stress resilience, and ecosystem service enhancement, culminating in yield stabilization and sustainable intensification. The framework emphasizes that productivity outcomes emerge from dynamic soil-plant-microbe interactions embedded within ecological, technological, and socio-economic contexts, thereby redefining yield gap analysis as a biologically regulated and systems-driven process rather than a purely input-dependent agronomic calculation. Biofertilizers influence plant productivity through multiple mechanisms including nitrogen fixation, phosphorus solubilization, phytohormone production, and disease suppression. These processes collectively enhance nutrient use efficiency and plant physiological performance.

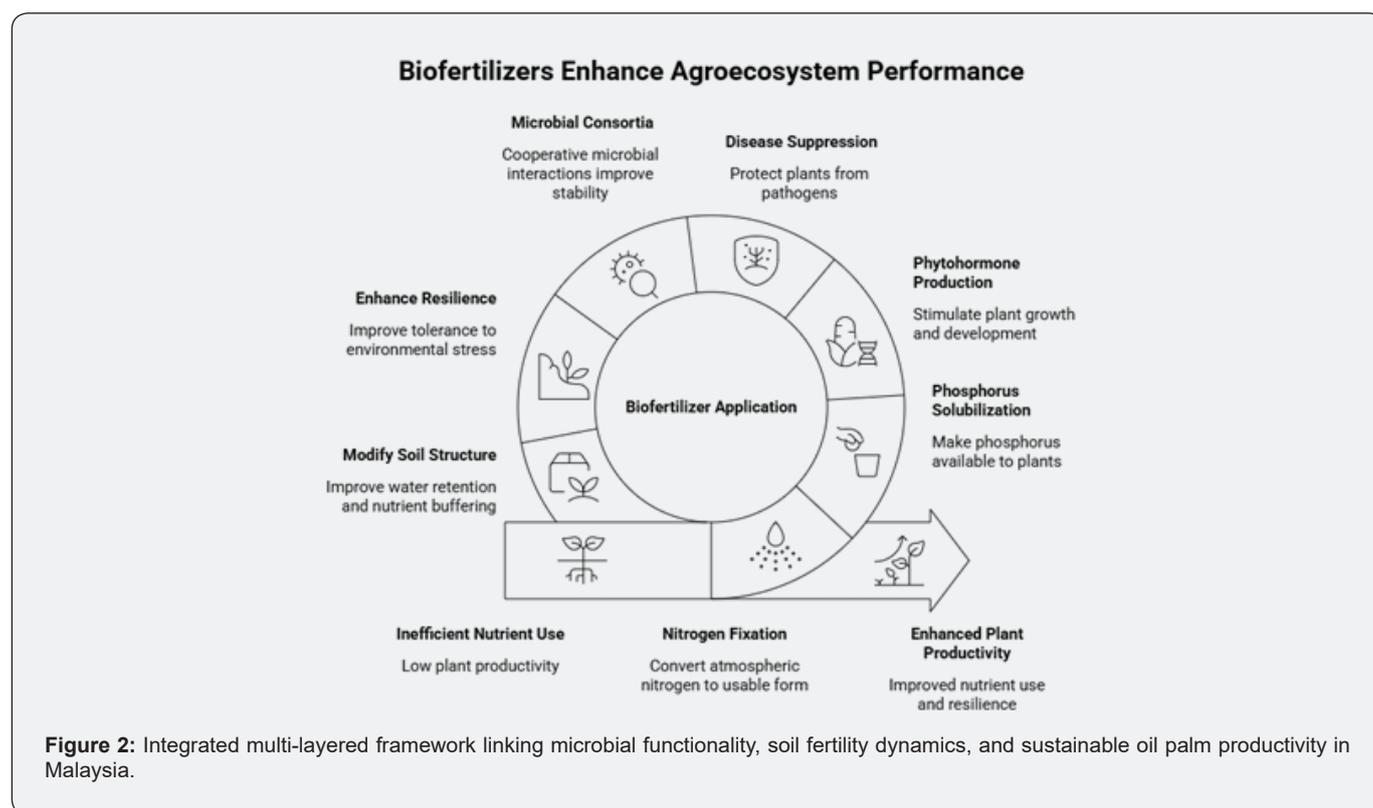


Figure 2: Integrated multi-layered framework linking microbial functionality, soil fertility dynamics, and sustainable oil palm productivity in Malaysia.

Empirical studies across crop systems demonstrate consistent yield improvement following biofertilizer application [3]. Microbial consortia represent a major innovation in biofertilizer design. Cooperative interactions among microbial species

improve functional stability and ecological compatibility within soil environments (Gouveia et al., 2025). Such consortia may be particularly relevant for oil palm systems where long crop cycles require sustained biological activity. Biofertilizers also enhance

plant resilience under environmental stress. Salt tolerance, drought resistance, and disease suppression have been linked to microbial inoculation (Borjian et al., 2025; Dalrymple & Punja, 2025). These adaptive benefits directly influence yield stability. Furthermore, biofertilizers modify soil structure and organic matter dynamics, improving water retention and nutrient buffering capacity (Kumar et al., 2025). Long-term soil improvement reduces productivity variability across seasons. Thus, biofertilizers function as systemic regulators of agroecosystem performance rather than simple nutrient supplements.

Circular Bioeconomy Integration in Oil Palm Systems

Figure 3 illustrates the interconnected flows linking biofertilizer application with circular resource recovery, ecological regeneration, and productivity enhancement within oil palm agroecosystems. It depicts how organic waste valorization, microbial activation, nutrient recycling, and soil health restoration interact to support plant growth, environmental sustainability, and long-term yield stability. The model emphasizes feedback loops between biological productivity, resource efficiency, and environmental performance, highlighting the transition from

linear input-dependent production toward regenerative, circular, and resilience-oriented agricultural systems. This systems perspective positions biofertilizers as central agents in integrating ecological processes with economic and sustainability objectives in modern oil palm cultivation. The integration of biofertilizers into oil palm production must be understood within a broader circular bioeconomy framework, where wastestreams are reconceptualized as nutrient resources. Oil palm plantations generate large volumes of organic residues, including empty fruit bunches, palm oil mill effluent, fronds, and kernel cake. Conventional management of these residues often leads to nutrient loss, greenhouse gas emissions, and suboptimal recycling efficiency. Emerging research in biofertilizer production demonstrates that agro-industrial and municipal waste streams can be biologically transformed into nutrient-rich soil amendments, thereby closing nutrient loops and reducing reliance on synthetic fertilizers [7] (Martín-Sanz-Garrido et al., 2025). Microalgae-based wastewater systems represent a particularly promising pathway. Studies show that microalgae cultivated in nutrient-rich wastewater not only remove pollutants but also generate biomass suitable for agricultural biofertilizer application [8,10].

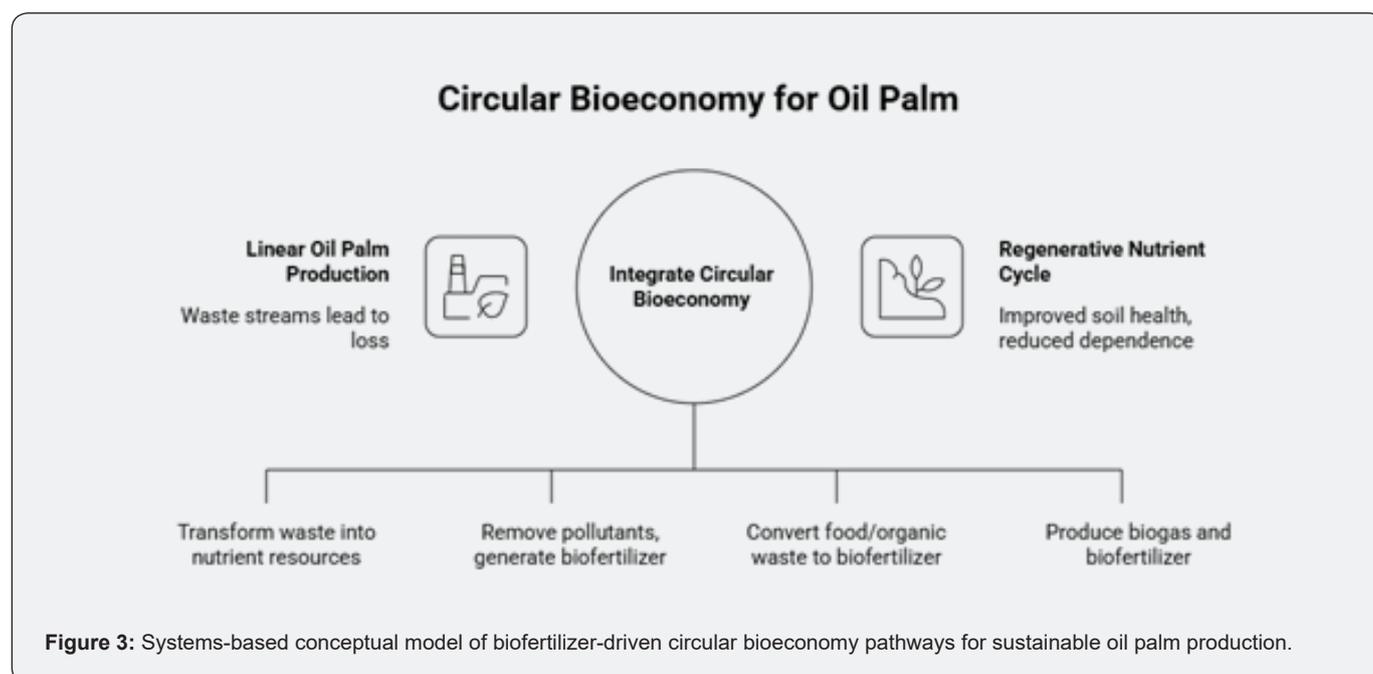


Figure 3: Systems-based conceptual model of biofertilizer-driven circular bioeconomy pathways for sustainable oil palm production.

Such systems simultaneously address nutrient discharge control and fertilizer production, providing dual environmental and agronomic benefits. In addition, carbon sequestration potential associated with microalgal biomass production enhances the climate relevance of these systems [9]. Food and organic waste valorization further strengthen circular integration. Conversion of food waste into biofertilizer and carbon sources for denitrification illustrates how zero solid discharge systems can be implemented through biological processing [7]. Similarly, mushroom waste has

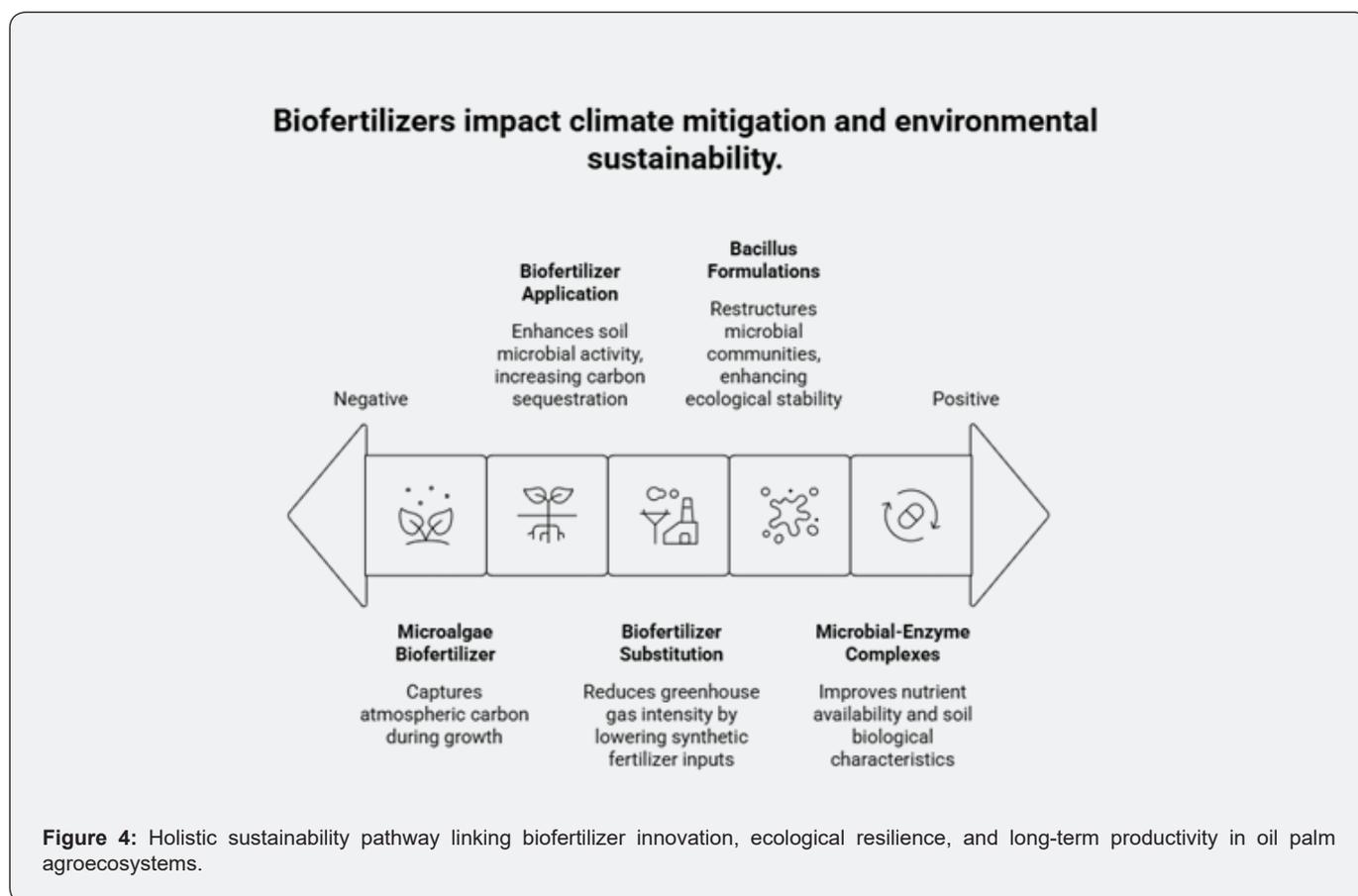
been optimized as a high-nitrogen biofertilizer source through multi-objective production design, balancing nutrient quality and economic feasibility [11,12]. These optimization strategies demonstrate that biofertilizer production is not merely a waste disposal solution but a technically refined resource transformation process. Animal manure and biowaste streams also provide opportunities for integrated nutrient recovery. Studies assessing biowaste potential for combined biogas and biofertilizer production highlight the importance of integrated waste

management systems that simultaneously produce renewable energy and organic fertilizers [13,14]. In oil palm contexts, similar integrated biogas-biofertilizer models could enhance nutrient recycling efficiency while reducing methane emissions from effluent ponds. The circular bioeconomy dimension therefore redefines oil palm productivity from a linear input-output model to a regenerative nutrient cycle model. Biofertilizers derived from local biomass resources can improve soil health, reduce external fertilizer dependence, and enhance environmental compliance. Integrating circular biofertilizer pathways into yield gap analysis provides a systemic understanding of productivity limitations that incorporates resource efficiency and environmental sustainability.

Climate Mitigation, Soil Carbon, and Environmental Sustainability

Figure 4 presents an integrative framework demonstrating how biofertilizer adoption supports multiple dimensions of sustainability through interconnected ecological, agronomic, and socio-economic processes. It illustrates the progression

from microbial enhancement and soil restoration to improved nutrient efficiency, plant health, environmental performance, and stable yield outcomes. The model emphasizes reinforcing feedbacks between resource efficiency, ecosystem resilience, and sustainable production, highlighting how biological inputs function not only as agronomic tools but as drivers of systemic transformation in oil palm management. This holistic pathway underscores the role of biofertilizer-based strategies in aligning productivity gains with environmental stewardship and long-term agricultural sustainability. Climate mitigation is increasingly central to agricultural policy and plantation management in Malaysia. Oil palm systems are scrutinized for greenhouse gas emissions, nutrient runoff, and soil carbon dynamics. Biofertilizers contribute to climate mitigation through improved nutrient use efficiency, reduced chemical fertilizer production emissions, and enhanced soil carbon stabilization [15]. Life cycle assessment studies demonstrate that biofertilizer substitution reduces overall greenhouse gas intensity in crop systems by lowering energy-intensive synthetic fertilizer inputs [15,16].



These reductions are particularly relevant for oil palm, where nitrogen fertilizer use constitutes a significant emission source. Additionally, research shows that biofertilizer application enhances soil microbial activity, leading to increased carbon

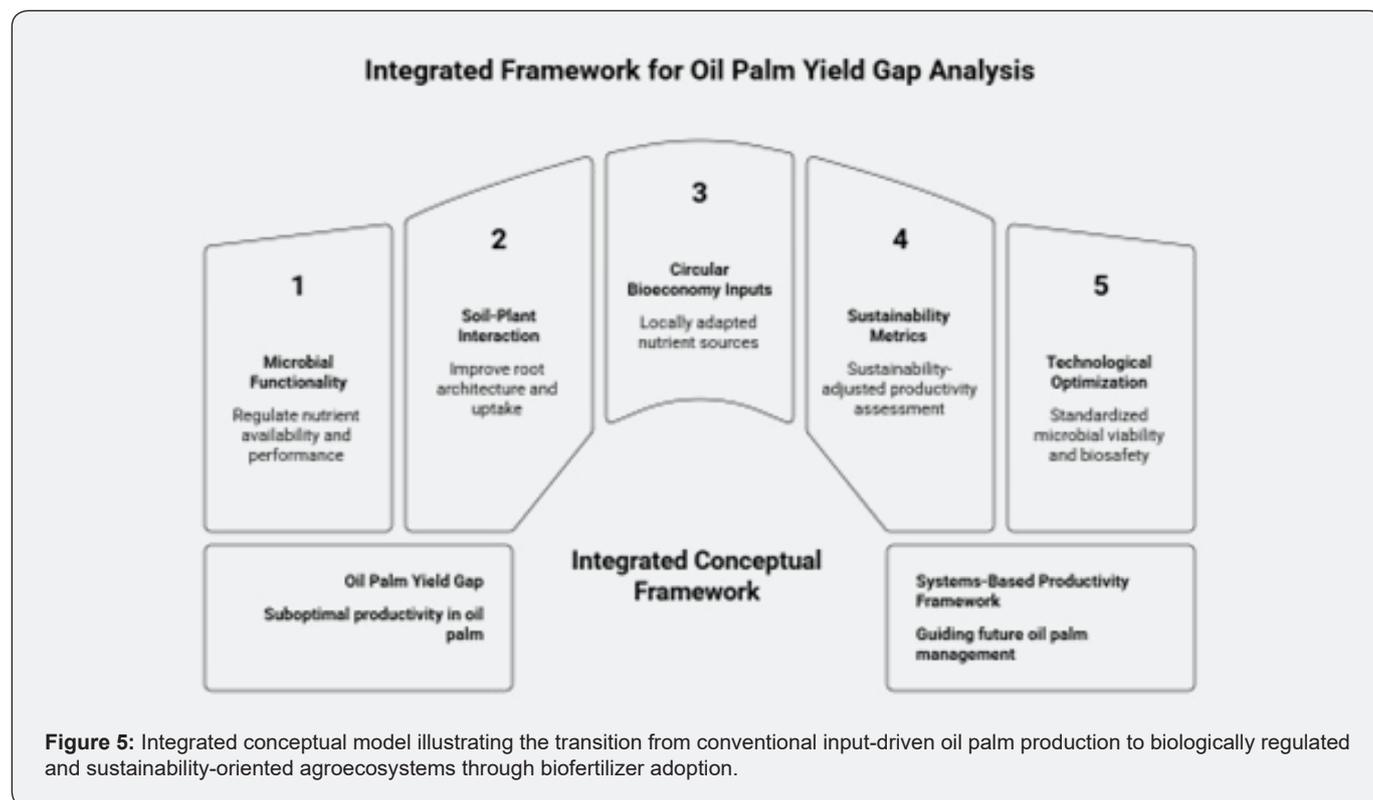
sequestration and improved soil organic matter dynamics [17]. Microalgae-based biofertilizer systems further contribute to atmospheric carbon capture during biomass growth [9]. When such biomass is applied to soils, part of the captured carbon

becomes incorporated into soil organic matter pools, potentially enhancing long-term carbon storage. This process aligns oil palm management with broader climate resilience strategies. Beyond carbon mitigation, biofertilizers support ecosystem health by reducing nutrient leaching and mitigating soil degradation. Bacillus-based formulations have been shown to restructure soil microbial communities and enhance ecological stability [2]. Similarly, integrated microbial-enzyme complexes improve nutrient availability and soil biological characteristics in degraded soils (Chen et al., 2026). These ecological improvements reduce the risk of environmental contamination and maintain productivity stability. Thus, biofertilizers serve as multifunctional agents that simultaneously enhance yield potential and environmental sustainability. Incorporating climate mitigation and soil carbon metrics into yield gap analysis ensures that productivity gains do not occur at ecological cost.

Proposed Integrated Conceptual Framework for Oil Palm Yield Gap Analysis

Figure 5 depicts a systems-level transformation pathway

in which biofertilizer application functions as a central driver of change across soil biological activity, nutrient cycling efficiency, plant physiological performance, and environmental sustainability outcomes. It highlights how the incorporation of microbial-based inputs promotes soil regeneration, resource recycling, and resilience to environmental stress, thereby shifting production systems away from dependence on synthetic inputs toward ecologically balanced and regenerative management. The model emphasizes interconnected feedback mechanisms linking productivity, ecosystem health, and resource efficiency, demonstrating how biologically mediated processes underpin long-term yield stability and sustainable intensification in oil palm cultivation. The integrated conceptual framework proposed here positions biofertilizers at the center of oil palm yield gap analysis, linking biological, technological, and environmental dimensions of productivity. The first layer of the framework focuses on microbial functionality, including nitrogen fixation, phosphorus solubilization, and phytohormone production [1,5]. These processes regulate nutrient availability and plant physiological performance. The second layer addresses soil-plant interaction dynamics.



Biofertilizer-induced improvements in root architecture, nutrient uptake efficiency, and stress tolerance directly influence bunch production and fruit yield [3] (Borjian et al., 2025). In long-cycle crops such as oil palm, sustained microbial functionality becomes critical for maintaining productivity across years. The

third layer integrates circular bioeconomy inputs. Waste-derived biofertilizers from mushroom residues, wastewater biomass, or manure systems provide locally adapted nutrient sources while reducing dependency on imported chemical fertilizers [8,11,13]. The fourth layer incorporates sustainability metrics,

including greenhouse gas intensity, carbon sequestration, and environmental footprint reduction [9,15]. These indicators transform yield gap analysis from a purely agronomic metric into a sustainability-adjusted productivity assessment. The fifth layer involves technological optimization and quality control. Effective biofertilizer performance requires standardized microbial viability, shelf life, and biosafety evaluation [18,19]. Multi-objective production optimization ensures economic feasibility without compromising biological efficacy [12]. Together, these five layers create a systems-based productivity framework capable of guiding future oil palm management strategies.

Implications for Malaysian Oil Palm Productivity

Figure 6 illustrates the interconnected constraints contributing to stagnating oil palm productivity by integrating biophysical, ecological, and socio-institutional factors within a single conceptual framework. It highlights how soil fertility decline, suboptimal nutrient cycling, and microbial imbalance collectively disrupt soil ecosystem functioning and limit plant growth through reduced nutrient availability and inefficient uptake. These biophysical challenges are further compounded by human and institutional limitations, including insufficient farmer knowledge and weak institutional support, which slow the adoption of biofertilizer-based management strategies. The model emphasizes that yield stagnation emerges from interacting biological and governance-related pressures, underscoring the need for integrated interventions that simultaneously address

soil health, microbial functionality, knowledge transfer, and policy support to restore productivity. Malaysia’s oil palm industry faces dual pressures of sustaining high yields and meeting global sustainability standards. Yield stagnation in mature plantations often reflects soil fertility decline, microbial imbalance, and suboptimal nutrient cycling rather than genetic limitations alone. Integrating biofertilizers into plantation management offers a pathway to restore soil biological function and reduce chemical dependency. Empirical evidence from multiple crop systems demonstrates consistent yield improvements under biofertilizer application [3] (Rahman et al., 2025). Although oil palm-specific long-term studies remain limited, the mechanistic processes identified across crops are transferable, particularly regarding nitrogen fixation and phosphorus mobilization. Adoption challenges must also be addressed. Studies show that farmer knowledge, perception, and institutional support influence biofertilizer uptake [20]. For oil palm estates and smallholders, extension services, demonstration trials, and economic incentives will determine implementation success. Policy alignment with circular bioeconomy initiatives can further accelerate adoption. Integrating mill effluent treatment with microalgae-based biofertilizer production could simultaneously reduce pollution and enhance soil fertility [10]. Such integrated systems support Malaysia’s sustainability certification frameworks. Thus, biofertilizers offer both agronomic and policy-level advantages for sustaining oil palm productivity under evolving environmental constraints.

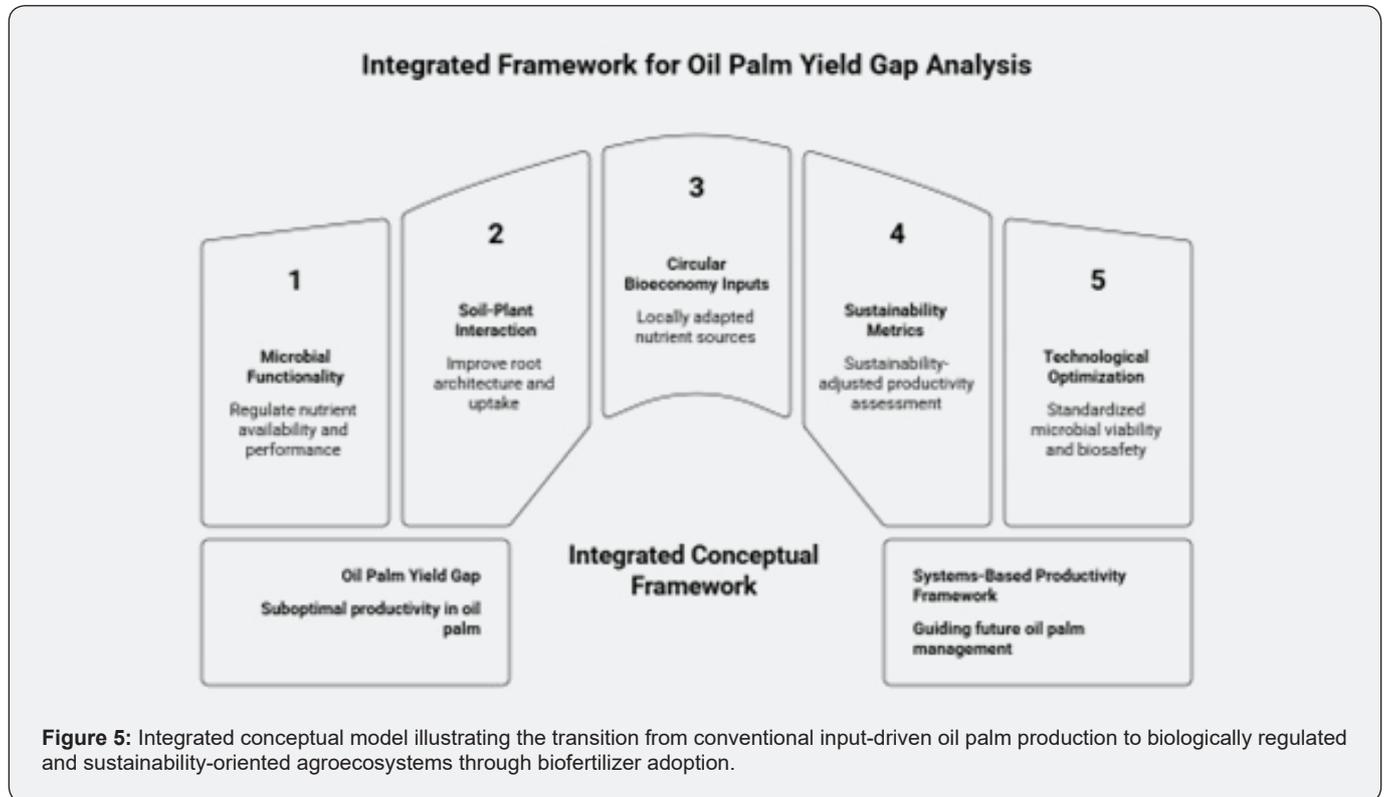
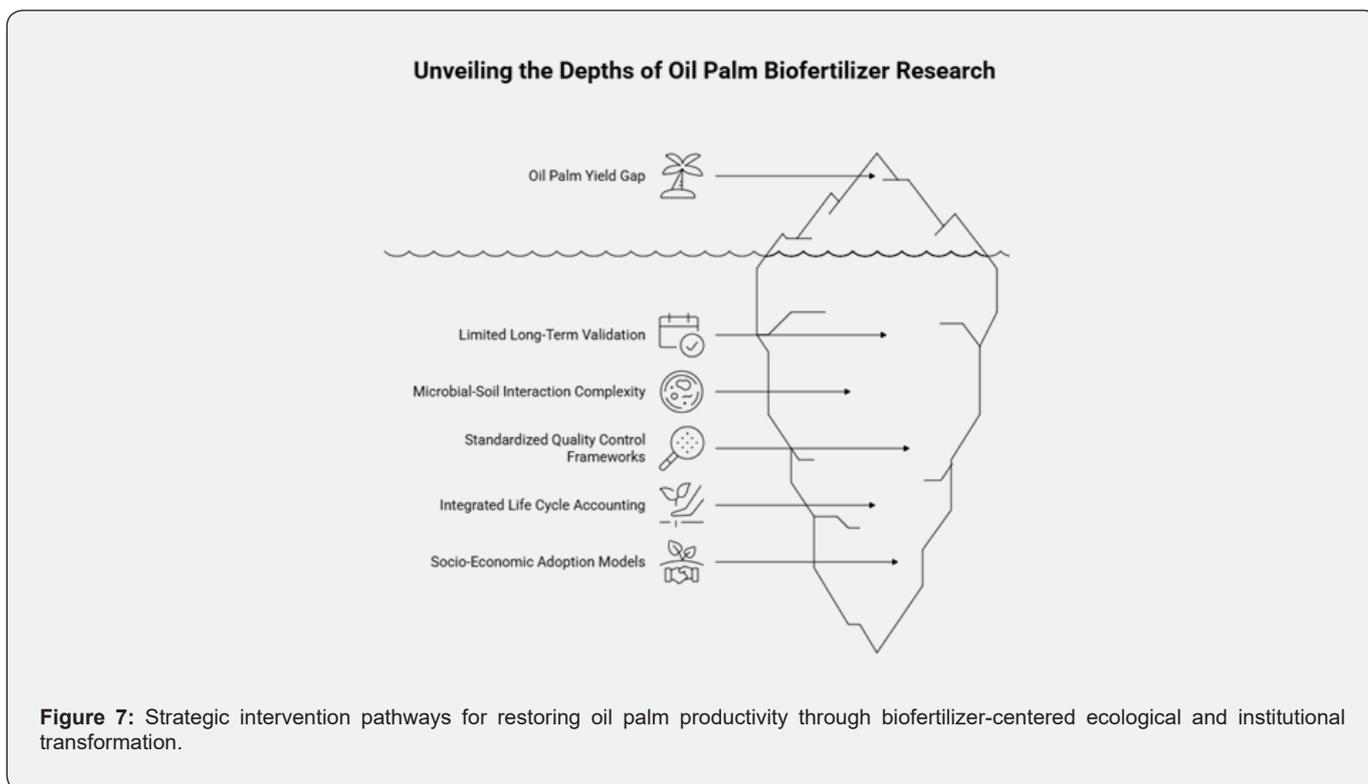


Figure 5: Integrated conceptual model illustrating the transition from conventional input-driven oil palm production to biologically regulated and sustainability-oriented agroecosystems through biofertilizer adoption.



Research Gaps and Future Directions

Figure 7 presents a solution-oriented framework outlining key intervention strategies to overcome yield stagnation in Malaysian oil palm systems by integrating biological restoration, knowledge development, and institutional strengthening. It illustrates how targeted actions such as enhancing soil fertility through biofertilizer application, rebalancing microbial communities, improving nutrient cycling efficiency, and strengthening farmer capacity and institutional support can collectively restore agroecosystem functionality. The model emphasizes coordinated responses across ecological, technological, and governance dimensions, demonstrating that sustainable productivity recovery depends on aligning scientific innovation with effective knowledge transfer and policy support to enable widespread adoption of biologically driven management practices. Despite strong scientific progress, several research gaps remain in applying biofertilizers to oil palm yield gap analysis. First, long-term field validation in perennial plantation systems is limited. Most studies focus on annual crops; therefore, multi-year trials in oil palm are necessary to evaluate sustained microbial performance [2]. Second, microbial-soil interaction complexity requires deeper ecological modeling. Synthetic community research provides insight into microbial compatibility and stability but needs scaling to heterogeneous plantation soils [6]. Third, standardized quality control frameworks must be strengthened. Ensuring consistent microbial viability, biosafety, and resistance monitoring is essential

for regulatory confidence and environmental safety [18,21]. Fourth, integrated life cycle and carbon accounting frameworks specific to oil palm biofertilizer systems are required to quantify climate mitigation benefits [15,16]. Fifth, socio-economic adoption models must complement biological research. Without farmer engagement and institutional support, technological innovation cannot translate into measurable productivity gains [20]. Future research should therefore integrate microbiology, agronomy, engineering, sustainability science, and policy analysis to create a comprehensive oil palm productivity model grounded in biological soil function.

Conclusion

Biofertilizers provide a powerful conceptual lens for reinterpreting productivity variation in oil palm systems. Rather than viewing yield gaps solely as agronomic inefficiencies, they reveal underlying biological and ecological constraints that shape nutrient availability, plant resilience, and soil functionality. By integrating microbial ecology, circular bioeconomy processes, and environmental sustainability into productivity analysis, biofertilizers redefine agricultural intensification as an ecosystem-based process rather than an input-driven strategy. This perspective is particularly relevant for Malaysia, where long-term plantation sustainability depends on maintaining soil health while meeting economic and environmental demands. The proposed conceptual framework positions biofertilizers as central regulators of agroecosystem performance and as diagnostic tools

for identifying biologically mediated yield limitations. Future oil palm productivity strategies should therefore integrate microbial management, resource recycling, and sustainability assessment within yield gap analysis. Such an approach supports resilient, low-carbon, and ecologically balanced plantation systems capable of sustaining productivity under future environmental and socio-economic challenges.

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