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A Circular Economy-Based Strategy for the Development of Biochar from Oil Palm Empty Fruit Bunches to Increase Added Value at PT Perkebunan Nusantara IV

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Abstract

This study aims to formulate a strategy for developing biochar from empty fruit bunches (EFB) waste based on a circular economy approach to increase the added value of PT Perkebunan Nusantara IV. As a large-scale palm oil plantation company, PTPN IV generates a significant volume of EFB from fresh fruit bunch processing. Current EFB utilization is still dominated by land application, incineration, and direct selling, which have not yet created optimal economic value for the company. This research applied a case study approach supported by qualitative and quantitative analysis through document review, interviews, limited observation, cost-benefit analysis, value-added analysis, risk analysis, and strategy formulation using SWOT and TOWS frameworks. The findings indicate that converting EFB into biochar has the potential to transform waste from a cost center into a value driver by reducing waste handling costs, partially substituting chemical fertilizer use, creating commercialization opportunities, and strengthening the company's environmental and ESG performance. Biochar development also supports the implementation of a closed-loop supply chain between palm oil mills and plantations, making it consistent with circular economy principles. The recommended implementation strategy includes conducting a pilot project, developing standard operating procedures and quality standards, strengthening human resource capacity, establishing technology partnerships, conducting agronomic validation, and implementing the program gradually in operational units with the highest readiness. Therefore, EFB-based biochar development can serve as a sustainable business strategy that supports operational efficiency, downstream development, and added value creation for PTPN IV.

INTRODUCTION

Palm oil is a national strategic commodity that has a major contribution to the Indonesian economy through the provision of vegetable oil, job creation, and the formation of added value in the agro-industrial sector (Wardhani & Rahadian, 2021; Harsono & Yuliana, 2021). The area of oil palm plantations which reaches around 16 million hectares shows the scale of this industry. As the production of fresh fruit bunches (FFB) increases, the volume of biomass waste produced is also increasing, so more efficient and sustainable management is needed to support the principles of sustainable development.

In the FFB processing process, palm oil mills produce various types of biomass such as empty oil palm bunches (TKKS), fiber, and shells. TKKS is one of the largest solid wastes with a proportion of around 22-23% of the total FFB processed (Phuang et al., 2022). The large volume of biomass shows that palm oil waste can no longer be seen as a residue that must be disposed of, but as a resource that has the potential to provide added value if managed properly (Bejarano et al., 2022; Sura & Ardi, 2023). Therefore, the use of biomass is an important issue in supporting resource efficiency and the sustainability of the palm oil industry (Supriatna et al., 2022).

PT Perkebunan Nusantara IV (PTPN IV) as one of the largest oil palm plantation companies in Indonesia also faces similar challenges. With a processing capacity of millions of tons of FFB each year, the company produces large quantities of biomass that require optimal management. Currently, the use of TKKS is still dominated by applications to land, limited burning, and direct sales. Although this method is able to reduce waste accumulation, the economic benefits generated are still relatively low and have not been able to optimize the added value potential of TKKS.

The circular economy approach offers a more comprehensive solution through the reuse of waste as a productive resource (Sura & Ardi, 2023; Abdul-Hamid et al., 2022). In this concept, TKKS is not only treated as waste that must be managed, but as raw materials that can be processed into products of economic value. The implementation of the circular economy has the potential to improve resource use efficiency, reduce environmental impact, and create new business opportunities that support company sustainability.

One potential form of utilization is the processing of TKKS into biochar through the pyrolysis process. Biochar has the benefit of being a soil conditioner that is able to improve soil quality, increase the efficiency of fertilizer use, and help store carbon in the long term. A number of studies have shown that the use of biochar can reduce the need for chemical fertilizers and provide significant operational cost savings. Thus, biochar has the potential to be a solution that not only solves the waste problem, but also increases the economic value of the company (Campion et al., 2023; El-Naggar et al., 2023).

Despite having great potential, the development of biochar from TKKS at PTPN IV still faces various obstacles. The results of problem identification show limitations in the aspects of human resources, management methods, equipment, raw material characteristics, performance measurement systems, and environmental factors. In addition, there is no integrated business model, comprehensive feasibility analysis, and clear implementation strategy to transform TKKS from a cost burden to a new source of revenue. This condition causes the use of TKKS to not provide optimal economic added value for the company.

The research gap lies in the absence of an integrated business model that captures two main value lines: cost saving and value capture. Cost savings arise from reducing the cost of handling TKKS and reducing part of chemical fertilizer inputs, while value capture comes from the creation of new income or economic benefits from biochar, liquid smoke, tar, as well as validated ESG value opportunities. The novelty of this study lies in the integration of circular economy principles with strategic management frameworks (SWOT, TOWS, and Balanced Scorecard) to develop a comprehensive implementation strategy for biochar development at PTPN IV.

Based on these conditions, this study aims to analyze the causes of the suboptimal use of TKKS, evaluate the potential for the development of biochar based on the circular economy, assess the technical, economic, operational, social, and environmental feasibility, and develop the right implementation strategy for PTPN IV. The research is limited to the use of TKKS as a raw material for biochar using the company's operational data in 2025. The results of the research are expected to be the basis for strategic decision-making in increasing added value, cost efficiency, and company sustainability through the development of biochar based on the circular economy.

METHOD

This study used a case study approach on PT Perkebunan Nusantara IV (PTPN IV/PalmCo) to analyze the development of the use of Empty Oil Palm Bunch (TKKS) waste into biochar based on the circular economy to increase the company's added value. The research approach combines qualitative and quantitative methods. The qualitative approach is used to understand the management conditions of TKKS, company policies, and biochar implementation strategies, while the quantitative approach is used to calculate the added value potential, fertilizer cost efficiency, and economic feasibility of the program. The research focused on one operational cluster consisting of palm oil mills and related plantations that were purposively selected based on the availability of data, TKKS volume, and relevance as an initial implementation location. Research data was obtained from internal company documents, interviews with key informants, field observations, and relevant literature and regulations.

The analysis is carried out in stages, starting from the identification of the existing conditions of TKKS management, the preparation of scenarios for the use of biochar in the framework of the circular economy, to the evaluation of its economic impact. Cost-Benefit Analysis and value-added analysis are used to measure the feasibility of the program as well as the potential for fertilizer cost savings and increased economic value of the company. Furthermore, a risk analysis is carried out to identify potential obstacles to implementation and its mitigation strategies. The results of all analyses are then synthesized through SWOT and TOWS analysis to formulate a realistic implementation strategy that is in accordance with the company's needs. The validity of the data is maintained through triangulation of sources, methods, and data, and supported by expert and management validation so that the research results can be used as a basis for strategic decision-making.

RESULTS AND DISCUSSION

Analysis of NPK Fertilizer Cost Efficiency through Biochar Application

One type of fertilizer that is widely used in oil palm plantations is NPK. (Anyaoha et al., 2022) Its use is large because this fertilizer functions to support plant growth and productivity. The type of NPK fertilizer used in oil palm plantations at PTPN IV is NPK: 13.6.27.4 + OTE, with a dose of 5.38 kg/tree/year (PTPN IV, 2023).

Generally, biochar is used as *a soil conditioner* or soil improvement agent. One of its functions is to suppress the loss of nutrients in the soil. Usually a lot of nutrients are carried when it rains through the erosion or leaching mechanism. Biochar can bind nutrients, so nutrients for plants to grow remain available. According to Ariani (2023), biochar is characterized by a high carbon content, stable in the soil and low ash content. The functions of biochar in agricultural land include: (1) carbon storage; (2) improving soil quality including sponges (cavities) to retain water and elements and nutrients (reduce nutrient leasing) and counteract soil acidity; (3) creating a good living place for microorganisms; and (4) increasing food crop production. (El-Naggar et al., 2023; Hasnain et al., 2024)

Furthermore, according to the research of Schmidt *et. al.* (2022), biochar produced at pyrolysis temperatures above 550°C and having an H:C ratio of less than 0.4 is very persistent when applied to soil. As much as 75% of this kind of biochar carbon is made up of stable polycyclic aromatic carbon and will survive more than 1,000 years after soil application, regardless of soil type and climate. The remaining 25% of biochar carbon can be considered semi-persistent, with an average residence in the soil of between 50 to 100 years, depending on the type of soil and climate (Rodrigues et al., 2023).

In addition to the function of biochar above, biochar can also replace part of the function of NPK fertilizer because biochar has a higher nutrient content of K and P than enriched TKKS and TKKS compost, and can reduce the use of NPK fertilizer dosage by up to 20-30% (Anyaoha et al., 2022; Hasnain et al., 2024). The recommended amount of biochar dosage for use in producing plants is 20kg/tree which is added every five years (Bumitama Gunajaya Agro, 2023).

The analysis of the cost of using biochar as *a soil conditioner* that can reduce the use of NPK fertilizer in oil palm plants is carried out by looking at the amount of fertilizer needed and fertilizer costs that must be incurred based on data on land area, number of trees, fertilizer needs per tree, price of NPK fertilizer, biochar production cost so that the total cost of NPK fertilizer without biochar can be calculated, and the savings that can be achieved by using biochar as a soil conditioner. The dose of using biochar as *soil conditioner* is 20kg/tree/5 years and the savings in the use of NPK fertilizer compared are (I) NPK fertilizer without Biochar, (II) NPK fertilizer + Biochar with a 20% reduction in NPK fertilizer use per year, (III) NPK + Biochar fertilizer with a 30% reduction in NPK fertilizer use per year. Important data and assumptions used in this cost analysis are the area of plantations: 109,410 hectares, the number of trees 13,159,196 trees, the need for NPK fertilizer is 70,793,775 Kg/year, the price of NPK fertilizer is Rp 12,000/Kg and the production cost of biochar from empty oil palm bunches is Rp 1,500/Kg.

The calculation of cost savings in using biochar as *a soil conditioner* can be seen in Table 6.13. The calculation results show that (I) the cost of 100% NPK fertilizer without the addition of biochar is IDR 849,525,300,000/year or IDR 7,764,604/hectare/year or IDR 64,558/tree/year; (II) the cost of NPK fertilizer (20% reduction in NPK use/year) + biochar is Rp758,586,078,323/year or Rp6,933,425/hectare/year or Rp57,647/tree/year; and (III) the cost of NPK fertilizer (30% reduction in NPK use/year) + biochar is IDR 673,633,548,323/year or IDR 6,156,965/hectare/year or IDR 51,191/tree/year.

Thus, the cost savings of NPK fertilizer with the addition of biochar as a *soil conditioner* for some biochar are (I) NPK fertilizer without biochar is IDR 0, (II) The reduction in NPK use by 20%/year is IDR 90,939,221,677/year or IDR 831,178/hectare/year or IDR 6,911/tree/year, and (II) The 30%/year reduction in NPK use is IDR 175,891,751,677/year or IDR 1,607,639/hectare/year or IDR 13,366/tree/year.

Table 1. Cost savings in the use of biochar as soil conditioner

Scenario 1 : NPK	
	Years 1 - 5
Reduction in NPK Use	0%
Fertilizer Requirement/Year (Kg)	70.793.775

Fertilizer Cost/Year	IDR 849,525,300,000
Fertilizer Cost/Hectare/Year	IDR 7,764,604
Fertilizer/Tree/Year Cost	IDR 64,558

Scenario 2 : NPK + biochar, 20%/year reduction in NPK usage						
	Year 1		Year 2		Year 3	
	NPK	Biochar	NPK	Biochar	NPK	Biochar
Reduction in NPK Use	20%	-	20%	-	20%	-
Fertilizer Requirement/Year (Kg)	56.635.020	263.183.920	56.635.020	-	56.635.020	-
Fertilizer Cost/Year	IDR679,620,240,000	IDR 394,829 .191.615	IDR679,620,240,000	IDR0	IDR679,620 .240.000	IDR0
	IDR 1,074,449,431,615		IDR679,620,240,000		IDR679,620,240,000	
Fertilizer/Tree/Year Cost	IDR 81,650		IDR 51,646		IDR 51,646	

Scenario 2 : NPK + biochar, 20%/year reduction in NPK usage (continued)				
	Year 4		Year 5	
	NPK	Biochar	NPK	Biochar
Reduction in NPK Use	20%	-	20%	-
Fertilizer Requirement/Year (Kg)	56.635.020	-	56.635.020	-
Fertilizer Cost/Year	IDR679,620,240,000	IDR0	IDR679,620,240,000	IDR0
	IDR679,620,240,000		IDR679,620,240,000	
Fertilizer/Tree/Year Cost	IDR 51,646		IDR 51,646	

Scenario 2 : NPK + biochar, 20%/year reduction in NPK usage (continued)	
Average Fertilizer Cost/Year	IDR758.586.078.323
Average Fertilizer Cost/Ha/Year	IDR 6,933,425
Average Fertilizer/Tree/Year Cost	IDR 57,647
Fertilizer Cost Savings/Year	IDR 90,939,221,677
Fertilizer Cost Savings/Ha/Year	IDR 831,178
Fertilizer/Tree/Year Cost Savings	IDR 6,911

Scenario 3 : NPK + biochar, 30%/year reduction in NPK use						
	Year 1		Year 2		Year 3	
	NPK	Biochar	NPK	Biochar	NPK	Biochar
Reduction in NPK Use	30%	-	30%	-	30%	-
Fertilizer Requirement/Year (Kg)	49.555.643	263.183.920	49.555.643	-	49.555.643	-
Fertilizer Cost/Year	IDR594,667 .710.000	IDR 394,829. 191.615	IDR594,667,710,000	IDR0	IDR594,667 .710.000	IDR0
	IDR 989,496,901,615		IDR594,667,710,000		IDR594,667,710,000	
Fertilizer/Tree/Year Cost	IDR 75,194		IDR 45,190		IDR 45,190	

	Year 4		Year 5	
	NPK	Biochar	NPK	Biochar
Reduction in NPK Use	30%	-	30%	-
Fertilizer Requirement/Year (Kg)	49.555.643	-	49.555.643	-
Fertilizer Cost/Year	IDR594,667,710,000	IDR0	IDR594,667,710,000	IDR0
	IDR594,667,710,000		IDR594,667,710,000	
Fertilizer/Tree/Year Cost	IDR 45,190		IDR 45,190	

Scenario 3 : NPK + biochar, 30%/year reduction in NPK use	
Average Fertilizer Cost/Year	IDR673,633,548,323
Average Fertilizer Cost/Ha/Year	IDR 6,156,965
Average Fertilizer/Tree/Year Cost	IDR 51,191
Fertilizer Cost Savings/Year	IDR175,891,751,677
Fertilizer Cost Savings/Ha/Year	IDR 1,607,639
Fertilizer/Tree/Year Cost Savings	IDR 13,366

The simulation results show that biochar can be a cost-efficiency instrument if the reduction of fertilizer dose is achieved and the cost of biochar can be controlled. In the first year, cash flow can be seen to be larger as biochar applications are carried out upfront for a five-year period (Nematian et al., 2021). Therefore, the analysis needs to differentiate between first-year cash flow and annual average costs. For the purpose of investment decisions, PTPN IV should use two views: first, an analysis of actual cash flows per year; Second, an annual average cost analysis to compare efficiency across scenarios.

Managerially, fertilizer savings have a strategic impact because fertilizer is one of the largest cost components in oil palm plantations (Campion et al., 2023). Even a small reduction in fertilizer doses can have a material impact on operational costs. However, such efficiency should not come at the expense of productivity. Therefore, the implementation of biochar must be accompanied by agronomic tests that measure soil response, nutrient status, plant growth, FFB production, and long-term effects.

Table 2 Aspects of agronomic validation before large-scale

Test aspects	Measured parameters	Purpose
Soil properties	pH, C-organic, cation exchange capacity, moisture, bulk density	Assessing the physical-chemical improvement of the soil due to biochar
Status hara	N, P, K, Mg, Ca, and microelements according to the needs of the garden	Ensuring fertilizer reduction does not cause deficiencies
Productivity	FFB/ha, weight of the bunch, number of bunches, yield when available	Proving that fertilizer efficiency does not decrease output
Dosage and method of application	kg/tree, frequency, application radius, combination with NPK	Define efficient operational recommendations
Application fee	Labor, tools, logistics, application time	Calculating the total cost of biochar in the garden
Environmental impact	Emissions, runoff, complaints, working area conditions	Supporting MRV and ESG KPIs

Added Value Analysis and Circular Value Creation

The added value in this study is not only interpreted as income from product sales. Added value should be calculated as a net economic benefit that arises as TKKS is converted from low-value or cost-effective materials to biochar that generates savings and/or revenue. Thus, the most suitable value-added model is the cost saving + value capture - additional processing cost model.

Added Value = Cost Saving + Value Capture - Additional Processing Cost

Cost savings can come from reducing the cost of managing TKKS, reducing transportation and hoarseness costs, reducing fertilizer costs, and potential energy efficiency. Value capture can come from the sale of biochar, liquid smoke, tar, or the utilization of carbon value if it has a legitimate methodology and market. (Xin et al., 2020; Bejarano et al., 2022) Additional processing costs include all additional costs to process TKKS into biochar, including CAPEX, OPEX, logistics, QC, and compliance costs. This model makes the analysis more comprehensive because it looks not only at the selling price of biochar, but also its contribution to the company's cost structure.

Table 3 Value-added model of the TKKS biochar program

Value components	Source of value	Formula/method of measurement	Notes
Cost saving 1	Reduction of TKKS handling costs	Baseline TKKS cost - TKKS cost after biochar	Need TKKS volume data diverted from land application/other patterns
Cost saving 2	Reduction of NPK fertilizer cost	Baseline fertilizer cost - biochar scenario fertilizer cost	Must be validated through agronomic tests
Value capture 1	Biochar sales	Volume sold x selling price	Need for quality and market specifications
Value capture 2	Sales of liquid smoke and tar	Volume sold x selling price	Need for marketability validation and permissions
Value capture 3	ESG/carbon value	tCO2e validated x economic value	Not financially calculated before MRV and clear market scheme

From the perspective of the Porter Value Chain, the biochar program expands PTPN IV's operational activities from just processing FFB to CPO and PK, to biomass management as a value-creating activity (Purnomo et al., 2020). From the perspective of the Resource-Based View, TKKS is a valuable internal resource because it is available continuously, has a large volume, and is difficult to replicate on the same scale by companies that do not have a PKS base and plantations as large as PTPN IV (Abdul-Hamid et al., 2022). However, TKKS only becomes a source of excellence when supported by the right capabilities: technology, human resources, SOPs, data, markets, and cross-functional governance.

Thus, the added value of biochar is multidimensional. First, operational value in the form of waste reduction and logistics improvements. Second, economic value in the form of cost savings and product revenue. Third, strategic value in the form of strengthening ESG, down streaming, and reputation. Fourth, the value of capabilities in the form of organizational learning in managing the circular economy. These four dimensions need to be reflected in KPIs Chapter V so that the program is not only assessed from one short-term financial indicator.

Environmental Impact Analysis and ESG

Biochar development has a direct relationship with PTPN IV’s environmental and ESG agenda. (Wardhani & Rahadian, 2021) The main expected environmental impacts are a reduction in unutilized TKKS, a reduction in potential emissions from biomass decay, an increase in carbon storage in the soil, a partial reduction in the use of chemical fertilizers, and an improvement in soil quality. The literature referenced in the manuscript, such as Schmidt et al. (2022), emphasize that the stability of biochar carbon is strongly influenced by production conditions, including pyrolysis temperature and biochar chemical characteristics. Therefore, environmental claims must be supported by explicit biochar and MRV quality data.

ESG impacts are not only related to the environment, but also to social and governance aspects (Mio et al., 2022). In the social aspect, the biochar program has the potential to create new jobs, improve human resource competence, and reduce public complaints related to odors or the accumulation of TKKS. In terms of governance, this program encourages companies to build a stronger recording system, ranging from material balance, cost, product quality, to emissions. Thus, biochar can be an instrument to strengthen PTPN IV's sustainability management system.

Table 4 Environmental and ESG indicators of biochar programs

ESG Dimension	Indicator	How to measure	Data needs
Environmental	Reduction of TKKS is not utilized	Tons of untapped TKKS baseline - actual	TKKS volume data and utilization categories
Environmental	Decrease in the use of chemical fertilizers	kg NPK baseline - actual	Fertilization data per plantation/per period
Environmental	Biochar carbon sequestration	tCO2e based on MRV methodology	Biochar carbon content, carbon stability, emission factors, system limits
Environmental	Reduction of odor/leachate complaints	Number of findings/complaints per period	K3 logs, housekeeping, community complaints
Social	Occupational safety and health	K3 findings, dust/smoke exposure, PPE, training	K3 audit and operational SOPs
Social	Job opportunities and competencies	Number of trained/engaged workforce	HR and training data
Governance	MRV maturity and KPI dashboard	Data completeness score and trail audit	Cross-functional reporting system
Governance	Regulatory and standard compliance	Permit status, SOP, certification, audit	Legal, regulatory and quality standard documents

In terms of discussion, environmental benefits should not be directly monetized before the MRV methodology is agreed. In the early stages, environmental benefits are enough to be reported as physical indicators, for example, tons of TKKS are utilized, tons of biochar are applied, kg of fertilizer is reduced, and soil quality testing results are achieved. Once the MRV system is mature, companies can consider monetizing carbon values or integrating them into the company's ESG reports.

Implementation Risk Analysis

Biochar programs have potential added value, but they also contain risks (Campion et al., 2023; Nematian et al., 2021). Key risks include technology risks, raw material risks, market risks, financial risks, agronomic risks, environmental risks, social risks, and governance risks. Risk analysis is important so that the implementation strategy not only emphasizes the benefits, but also anticipates factors that can thwart the achievement of added value.

The method used is the Probability x Impact Matrix with a scale of 1 to 5. The risk with a score of 1-4 is categorized as low, 5-9 moderate, 10-15 high, and 16-25 very high. The following scores are preliminary drafts and need to be validated through discussions with PTPN IV management, technology vendors, and pilot operational units.

Table 5 Risk register of the initial TKKS biochar program

Risks	Prob.	Impact	Score	Category	Key mitigations
Biochar yield is lower than assumed	3	4	12	Height	Pilot test, vendor performance contract, material balance monitoring
OPEX is higher than assumed	3	4	12	Height	Sensitivity analysis, control energy, preventive maintenance
The liquid smoke/tar market is not absorbed	3	3	9	Medium	Off taker validation before large-scale investment
Biochar quality is inconsistent	3	4	12	Height	SOP feedstock, QC per batch, internal quality specification
Fertilizer reduction is not achieved in the field	3	5	15	Height	Phased agronomic test, dose control, productivity evaluation
Uncontrolled pyrolysis process emissions	2	5	10	Height	Low emission technology, scrubber/afterburner, emission monitoring
Conflict between the allocation of TKKS and the needs of the plantation/other parties	3	3	9	Medium	TKKS allocation policy and cluster priorities
Incomplete KPI data	4	3	12	Height	Cross-functional dashboard, data PIC, trail audit
Delays in permits or regulatory compliance	2	4	8	Medium	Legal review and licensing fulfillment from the design stage
Operational/HR resistance	3	3	9	Medium	Training, SOPs, KPI incentives, cross-functional forums

The highest risk in the early stages is not only technological risk, but the risk of not achieving the assumed economic benefits. For example, if biochar is not able to reduce fertilizer use according to the scenario, the cost saving benefits will decrease significantly. Similarly, if the liquid smoke and tar market is not ready, the combined B/C ratio will be lower. Therefore, the implementation strategy should place the pilot as a technical, agronomic, financial, and market proof stage simultaneously.

Table 6 Risk control priorities by implementation phase

Phase	Dominant risk	Recommended controls
Pra-pilot	Incorrect location selection, incomplete baseline data, inappropriate vendor	Data-based site selection, vendor due diligence, cost baseline and material balance
Production pilot	Low yield, high downtime, emissions, inconsistent quality	Performance test, SOP operation, QC batch, preventive maintenance, emission measurement
Garden app pilot	Improper dosage, no agronomic response, high application cost	Agronomic test design, control plot, soil and productivity monitoring, application cost evaluation
Early commercialization	The market does not absorb the product, the price drops, the distribution costs are high	MoU/offtake, quality specifications, market testing, phased sales channels
Scale-up	Cross-functional coordination is weak, KPIs are not monitored, investment is out of control	PMO, dashboard KPI, stage-gate investment, audit internal

Strategy Analysis: SWOT and TOWS

SWOT analysis is used to summarize internal and external factors that influence the development of TKKS biochar (Usapein et al., 2022). The main strengths of PTPN IV are the scale of TKKS supply, the integration of PKS-plantation, the large need for fertilizers, and the alignment of the program with the vision of sustainability and down streaming. The weakness lies in the need for CAPEX, technology readiness, TKKS moisture content, incomplete cost-benefit data, and the need for cross-functional coordination. External opportunities include the demands of the circular economy, the market for environmentally friendly products, the potential for reducing imported fertilizers, and strengthening ESG. Threats include market fluctuations, technological risks, regulatory changes, and competition with alternative products.

Table 8 SWOT analysis of PTPN IV TKKS biochar development

Strengths (S)	Weaknesses (W)
1. The supply of TKKS is very large and continuous. 2. PTPN IV has a PKS-plantation integration that supports closed-loop. 3. The need for fertilizer is high so the potential cost savings are significant. 4. The program is aligned with the vision of sustainability, down streaming, and ESG. 5. Related units are available: Sustainability, Down streaming, Plant, Operational, Finance.	1. TKKS has a high-water content, so pre-processing and logistics costs are large. 2. Efficient pyrolysis technology requires significant CAPEX and OPEX. 3. Agronomic cost and benefit baseline data is incomplete. 4. QC, SOP, and MRV biochar do not exist yet. 5. The by-product market needs to be proven.
Opportunities (O)	**Threats (T)**
1. Encouraging circular economy and zero waste. 2. Opportunity for partial substitution of chemical fertilizers. 3. Biochar market and eco-friendly products. 4. Potential ESG and carbon value if MRV is valid. 5. Technology and offtake partnership opportunities.	1. Fluctuations in the price of biochar, liquid smoke, tar, and fertilizer. 2. Risks of low-efficiency or high-emission technologies. 3. Changes in regulations or quality standards. 4. Unattainability of agronomic benefits. 5. Organizational resistance and scale-up complexity.

The SWOT results need to be downgraded to the TOWS strategy so that the recommendations are more operational. The SO strategy leverages internal strengths to seize opportunities. The WO strategy uses external opportunities to improve internal weaknesses. ST's strategy utilizes power to deal with threats. The WT strategy focuses on protection and risk reduction.

Table 9 TOWS Matrix TKKS biochar implementation strategy

Types of strategies	Strategy formulation	Priority Programs
SO – using force to seize opportunities	Building a pilot closed-loop PKS-plantation in clusters with a surplus of TKKS and high fertilizer needs.	Pilot one PKS 60 tons/hour; application of biochar in nearby gardens; Economic-operational-environmental KPI dashboard.
SO – downstream	Developing a portfolio of biochar, liquid smoke, and tar products as a biomass downstream line.	Quality specifications, market studies, off taker MoU, product tests, certifications when required.
WO – fixing weaknesses through opportunity	Leverage technology partnerships to reduce CAPEX risks and ensure	Vendor due diligence, trial performance, lease/operation cooperation scheme,

	emissions are controlled.	knowledge transfer.
WO – data and MRV	Build an MRV system and dashboard since the pilot so that value-added and ESG claims can be audited.	Material balance, cost/ton, QC, emissions, fertilizer, productivity, and periodic reports.
ST – use force in the face of threats	Leverage supply scale and farm integration to reduce dependence on external markets.	Prioritize the internal use of biochar before external sales expansion.
ST – market control	Reduce price risk with offtake contracts and product diversification.	Price contracts, domestic-export sales options, stock and distribution strategies.
WT – defensive	Conducting stage-gate investment so that scale-up is only carried out after the pilot meets the KPIs.	Gate 1 baseline, Gate 2 technical test, Gate 3 agronomic test, Gate 4 commercialization, Gate 5 scale-up.
WT – operational mitigation	Establish SOPs for emissions, K3, quality, and logistics before full operation.	SOP for operation, maintenance, PPE, dust/smoke control, K3 and environmental audits.

Summary of Analysis and Discussion Results

Based on all analyses, the development of biochar from TKKS based on *the circular economy* deserves to be positioned as a strategy to increase PTPN IV's added value. The main reason is that PTPN IV has a large and continuous supply of TKKS, significant fertilizer cost efficiency needs, and a strategic mandate to strengthen downstream and sustainability. The biochar program addresses these three needs through a closed-loop model that connects mills, biomass processing units, and gardens.

Economically, preliminary simulations show that biochar units can produce a B/C ratio above 1. Feasibility becomes stronger when liquid smoke and tar by-products can be monetized. On the garden side, simulations show the potential for significant cost savings of NPK fertilizers in the 20%-30% reduction scenario, but these benefits must be validated through rigorous agronomic tests. Thus, the biochar program should not be immediately decided as a full scale-up, but through a scalable pilot with stage-gate investment.

Strategically, biochar changed the position of TKKS from *a cost center* to a *value driver*. The value created is not only product revenue, but also cost savings, waste reduction, ESG strengthening, increasing *circular economy* capabilities, and supporting PTPN IV's vision as a global, integrated, and sustainable agribusiness company. Therefore, the main recommendations are to run a TKKS biochar pilot in selected PKS-plantation clusters, build data systems and MRVs from the beginning, validate agronomic and market benefits, and conduct a gradual scale-up based on KPIs.

The circular economy-based biochar development strategy from Empty Oil Palm Bunch (TKKS) waste has broad managerial implications for PT Perkebunan Nusantara IV (PTPN IV). This strategy is not only related to waste treatment, but also concerns changes in the way companies view TKKS as an internal resource that can create cost efficiency, new revenue opportunities, ESG strengthening, and biomass down streaming. Thus, the biochar program needs to be managed as a cross-functional business transformation initiative, not as a stand-alone technical project.

The results of the previous analysis showed that PTPN IV has a large and sustainable supply of TKKS, but its utilization still faces strategic, operational, economic, and environmental constraints. The root of the main problem lies in the lack of an integrated business model that is able to capture two main value lines, namely cost saving and value capture. Cost savings arise from reducing the cost of handling TKKS and reducing part of chemical fertilizer inputs, while value capture comes from the creation of new income or economic benefits from biochar, liquid smoke, tar, as well as validated ESG value opportunities.

The use of the Balanced Scorecard (BSC) framework, so that the proposed strategy can be translated into measurable managerial actions. The BSC approach helps management map the contribution of biochar strategies to organizational performance in a more balanced manner through four perspectives, namely *Financial, Internal Business Process, Learning & Growth (People),* and *Customer & Stakeholders*. These four perspectives are interconnected in a cause-and-effect relationship: strengthening HR and data capabilities drives better internal processes, good processes increase customer and stakeholder trust, and ultimately generate financial value for the company.

Managerial Implications Based on *a Balanced Scorecard*

The Balanced Scorecard in the biochar program functions as a system for translating strategies into organizational goals, KPIs, targets, and responsibilities (Mio et al., 2022; Jassem et al., 2022). In the context of PTPN IV, BSC not only measures short-term financial success, but also ensures that process readiness, HR competence, farm revenue, market validation, and ESG compliance run simultaneously. This is important because the success of biochar is determined by factory-garden integration, economic feasibility, agronomic validation, and cross-functional governance.

Table 10 presents a Balanced Scorecard design for managing TKKS biochar development strategies. The KPIs in the table are managerial and need to be readjusted to the actual data of the pilot, company policies, and the results of agronomic and market validation.

Table 10 Balanced Scorecard for PTPN IV TKKS Biochar Development

Perspective	Strategic Goals	Managerial Implications	Key KPIs	Measurement Target/Direction	Person in Charge
Financial	Transforming TKKS from cost center to value driver	The Board of Directors needs to establish a biochar business case that separates cost saving, value capture, and additional processing costs.	Net added value; Net Benefit; B/C Ratio; ROI; Payback Period	The pilot is declared eligible if the B/C Ratio is > 1, the Net Benefit is positive, and the main sensitivity is controlled.	Board of Directors; Finance & Risk Management; Downstream
Financial	Cost efficiency of NPK fertilizer	Biochar is used as a soil conditioner based on agronomic tests, not just an administrative substitution of fertilizers.	Savings in NPK costs; kg NPK is reduced; fertilizer costs/ha/year; Fertilizer/tree/year cost	Validate the scenario of reducing NPK by 20%-30% in pilot units without reducing productivity.	Crop Division; Finance; Sustainability
Financial	Monetization of biomass	Biochar, liquid smoke, and tar	Product revenue; margin/ton; volume	Commercialization is expanded	Downstreaming; Marketing;

	downstream products	products are positioned as biomass downstream portfolios with pricing and offtaker strategies.	sold; amount of MoU/offtake	once quality, market, and positive margin specifications are proven.	Finance
Financial	Investment risk control	CAPEX is not released all at once, but through a stage-gate based on technical, agronomic, financial, and market evidence.	Status gate; CAPEX/OPEX deviation; the results of sensitivity analysis; Realization of Payback	Scale-up is only done if the pilot meets the minimum KPIs and the high risk drops to a controlled level.	Board of Directors; PMO Biochar; Risk Management
Internal Business Process	Closed-loop supply chain PKS-kebun	The TKKS flow is mapped from mills, pre-processing, pyrolysis, garden applications, commercialization, to MRV.	% TKKS processed; tons of TKKS in units; material balance; Logistics Cost/Ton	The pilot's material balance is recorded 100% each period and is used as the basis for operating decisions.	PKS Operations; Plants; Downstream
Internal Business Process	Standardization of pre-process and quality of biochar	Companies need SOPs for moisture content, shredding, drying, pyrolysis temperature, batch QC, storage, and garden applications.	Kadar air feedstock; rendemen; QC pass rate; mutu biochar; downtime	Each batch has a QC record and quality deviations are followed up through corrective action.	Operational; QC; Technology Vendors
Internal Business Process	ESG, K3, and compliance integration	Controlling emissions, dust, odors, leachate, permits, and occupational safety must be part of the process design from the beginning.	Permission status; K3 findings; emission monitoring results; complaints of odor/leache; Housekeeping audit	There were no major violations of K3/environment and all operations followed compliance SOPs.	Sustainability; K3; Legal; Operational
Internal Business Process	Cross-functional performance dashboard	Data on production, cost, quality, emissions, fertilization, and productivity must be included in an auditable dashboard.	Data completeness; timeliness of reporting; the number of KPIs filled; Audit trail	The pilot dashboard is active from the beginning of operation and is reviewed at least monthly.	HR & IT; PMO; Finance; Sustainability
Learning	Improving	Operators,	The number of	All pilot and	HR & IT;

& Growth (People)	HR competencies	technicians, agronomists, cost analysts, and sustainability teams need to be trained on biochar, pyrolysis, QC, MRV, and CBA.	human resources trained; training hours; competency scores; Internal Certification	core operator PICs are declared competent before limited commercial operations.	Vendors; Operational; Plants
Learning & Growth (People)	Culture of innovation and cross-functional collaboration	The biochar program must be managed as a cross-functional business transformation so that it is not trapped in the silos of mills, plantations, downstreaming, and sustainability.	Frequency of cross-functional forums; the number of improvement initiatives; Cross-functional issue resolution	The PMO forum runs regularly and each critical issue has a PIC and a deadline for resolution.	Board of Directors; PMO; All Related Divisions
Learning & Growth (People)	Circular KPI-based incentives	Biochar KPIs need to be linked to the unit scorecard so that efficiency, quality, data, and safety behaviors are consistently driven.	Biochar KPIs entered into performance contracts; the achievement of unit KPIs; SOP compliance	The pilot KPIs are integrated into the relevant unit scorecard once the BSC design is approved.	Board of Directors; HR & IT; Finance
Customer & Stakeholder	Adoption by the farm as an internal customer	The Crops and orchard divisions should be treated as internal customers assessing the benefits of biochar on soil, fertilizer, and productivity.	Application plot area; adoption rate; soil test results; productivity response; Garden satisfaction	Applications are extended only to locations that demonstrate agronomic benefits and do not interfere with productivity.	Crop Division; Estate Manager; Research/Agronomy
Customer & Stakeholder	External market validation	Before scale-up, external customer needs, quality specifications, prices, and distribution channels must be validated.	Number of potential customers; MoU/offtake; market test volume; Complaint Rate	At least there is proof of market absorption or offtake for products that are not used internally.	Downstreaming; Marketing; Legal
Customer & Stakeholder	Strengthening ESG reputation and public relations	The biochar program must reduce environmental complaints,	Community complaints; ESG indicators; MRV reports; audit results; Certification/Compli	There are no major complaints that go unresolved and the	Sustainability; Institutional Relations; Operational

	strengthen ESG reporting, and demonstrate contribution to the circular economy.	ance Status	program's ESG data can be audited.

Source: Data processed, as well as Kaplan and Norton's Balanced Scorecard framework.

Implications on Financial Perspectives

From a financial perspective, the biochar program changes the position of TKKS from a cost center to a value driver. As long as TKKS is only managed through handover, limited combustion, or sale of raw materials, the value obtained by the company is relatively limited and a portion of the handling costs remain incurred. Through processing into biochar, TKKS has the opportunity to generate value through two mechanisms, namely cost reduction and capture the value of new products.

The first implication for management is the need to prepare a business case that separates the components of cost saving, value capture, and additional process costs. Cost savings include savings in the cost of handling TKKS, transportation, hoarseness, and the potential to reduce the cost of NPK fertilizer. Value capture includes potential revenue from biochar, liquid smoke, tar, or ESG benefits that can be monetized if MRV and market methodologies are available. Additional processing costs include CAPEX, OPEX, labor, energy, maintenance, logistics, QC, as well as environmental compliance costs.

The second implication is the need for a phased investment approach. The results of the initial simulation show that the biochar unit has the potential to have a B/C Ratio above 1, both for biochar alone and for biochar and by-products. However, this feasibility is very sensitive to selling prices, yields, OPEX, downtime, and market absorption of by-products. Therefore, investment decisions should not be directly entered into full scale, but are carried out through pilot and stage-gate investment. Each gate must test technical, agronomic, financial, market, and environmental compliance.

The third implication is the integration of the financial KPIs of the biochar program into the RKAP and the performance contracts of related units. Indicators such as fertilizer cost savings, B/C Ratio, ROI, payback period, added value per ton of TKKS, and downstream product revenue need to be part of the management evaluation. In this way, biochar not only becomes an innovation program, but becomes an instrument of cost control and accountable value creation.

Implications for the Internal Business Process Perspective

From the perspective of the Internal Business Process, the biochar strategy requires a change in the process from waste management to resource value management. It is not enough for companies to simply move TKKS from factories to farms, but need to build a closed-loop supply chain that connects mills, pre-processing units, pyrolysis units, farms, product downstreams, and MRV systems. This flow is at the heart of the circular economy because materials that previously ended up as waste are returned to productive inputs.

The first process implication is the need to standardize material flow. Fresh TKKS has a high moisture content so it is expensive to transport and inefficient to be directly carbonized.

Therefore, the location of the processing unit needs to be chosen as close as possible to the PKS or the source cluster of TKKS. Preprocesses such as pressing, chopping and drying must be the raw process so that the moisture content, volume, and quality of raw materials are more controlled.

The second process implication is the implementation of quality control. The quality of biochar will determine the success of the plantation application and market acceptance. Therefore, each batch of biochar needs to be tested against minimal parameters such as moisture content, ash content, pH, particle size, carbon content, and contaminant potential. QC also needs to be applied to by-products such as liquid smoke and tar when they are to be commercialized.

The third process implication is operational integration between units. PKS is responsible for the supply of TKKS and the initial pre-processing; the biochar unit is responsible for the production process; The Crops Division is responsible for the application and measurement of agronomy; The Sustainability Division oversees MRV and ESG compliance; The Downstream Division develops the market; and the Finance Division calculates eligibility. Without the integration of these processes, the economic and environmental benefits of the program will be difficult to prove.

Implications on Learning & Growth Perspective (People)

From a Learning & Growth perspective, the biochar program requires strengthening human resource capabilities, innovation culture, and data systems. Biochar is a new initiative that combines aspects of agronomy, process technology, biomass logistics, finance, ESG, K3, and downstreaming. Therefore, implementation cannot rely solely on existing operational experience, but requires structured organizational learning.

The first implication is the need for cross-functional training programs. Operators and technicians need to understand pre-process, pyrolysis, maintenance, K3, emission control, and QC processes. The plant team needs to understand the dosage, application method, test plot design, soil monitoring, and productivity evaluation. Finance teams need to understand the separation of baseline costs and intervention costs, while sustainability teams need to understand MRV and ESG reporting.

The second implication is the formation of a data-driven work culture and collaboration. A prone biochar program fails when each unit works on its own indicators without looking at the value chain as a whole. Therefore, companies need to form a Project Management Office (PMO) or cross-functional team that has a clear mandate, regular meeting schedule, risk register, KPI dashboard, and authority to resolve operational obstacles.

The third implication is the alignment of incentives. If the plantation's KPIs only emphasize short-term productivity, then the adoption of biochar could face resistance as it is considered to add jobs. Conversely, if the biochar program's KPIs only emphasize production volumes without agronomic quality and benefits, then the program risks not creating value. Therefore, KPIs must balance productivity, cost efficiency, quality, safety, and completeness of data.

Implications on Customer & Stakeholder Perspectives

In the biochar program, the customer doesn't just mean an external buyer. The main customer in the early stages is an indoor garden that uses biochar as a soil conditioner. Therefore, the success of the strategy is not only measured by the volume of biochar produced, but also by the acceptance of the plantation, ease of application, impact on the soil, reduction in fertilizer use, and the absence of a decrease in productivity.

The first implication is the need for value validation for internal customers. The Crop and Garden Division need to be involved from the pilot design stage so that the dose, application time, application tools, labor needs, and agronomic indicators are mutually agreed. The test plot needs to have a clear comparator so that the benefits of biochar can be objectively proven.

The second implication is the validation of external markets. If biochar, liquid smoke, and tar are to be sold, the company needs to determine product specifications, customer segments, prices, minimum volumes, contract schemes, and regulatory or certification requirements. Commercialization should not be the main financial assumption until there is sufficient evidence of demand or offtake.

The third implication is the strengthening of stakeholder relationships. The biochar program can strengthen PTPN IV's reputation in sustainability because it contributes to waste reduction, carbon storage potential, partial reduction of chemical fertilizers, and control of environmental complaints such as odors or leachate. However, environmental claims must be supported by MRV data to be credible for auditors, regulators, shareholders, and the surrounding community.

Balanced Scorecard *Causal Relationship Map*

The cause-and-effect relationship in BSC shows that financial results do not stand alone. Cost savings and new revenue will only occur if HR is competent, internal processes run stable, internal customers receive biochar, external markets are validated, and ESG data can be audited. A map of the cause-and-effect relationship of the biochar program is presented in Table 11

Table 11 Causal Relationship Map of the BSC Biochar Program

No.	Learning & Growth	Internal Business Process	Customer & Stakeholder	Financial Outcome
1	Trained human resources, understood SOPs, and active dashboards	Preprocessing, pyrolysis, QC and garden application processes become stable	Biochar can be accepted by gardens and used as soil conditioner	NPK savings, reduced TKKS costs, and increased added value
2	MRV capabilities and cost data built since the pilot	Material balance, emissions, quality, and cost/ton recorded	ESG claims are more credible for regulators, auditors, and stakeholders	Investment risk decreases and carbon/ESG value opportunities are more open
3	PMO and stage-gate mechanism running	CAPEX, OPEX, downtime, and quality risk are controlled	Offtakers and internal customers obtain consistent supply	ROI is more maintained and expansion can be carried out gradually

Source: Data processed

Implementation Governance and Accountability Implications

In order for the biochar program to run effectively, companies need to establish clear governance. These initiatives involve a wide range of functions, so the risk of coordination becomes high if there is no program owner responsible for the entire value chain. The recommended governance is the formation of a steering committee at the Board of Directors level and the Biochar PMO at the cross-functional operational level.

The role of the steering committee is to set strategic direction, approve resource allocation, and decide on the continuation of investment at each gate. The PMO plays a role in coordinating daily implementation, monitoring KPIs, managing risk registers, preparing management reports, and ensuring that each function performs its role. The draft division of managerial roles is presented in Table 12.

Table 12 Design of Unit Roles in Biochar Program Governance

Units/Functions	Main Role	Accountability Output
Board of Directors/Steering Committee	Providing strategic mandates, approval of investment gates, and alignment of programs with the vision of sustainability and downstreaming.	Investment decisions, KPI approvals, and strategic risk control.
PMO Biochar	Coordinate cross-functional work, monitor BSC KPIs, manage risk, and report on periodic progress.	Dashboard, risk register, monthly reports, and gate recommendations.
Business Development & Downstream Division	Develop business models, market validation, product specifications, and commercialization strategies.	Business case, MoU/offtake, product portfolio, and pricing strategy.
Operations of the Cooperative	Ensuring the supply of TKKS, pre-processing, internal logistics, and processing unit operations according to SOPs.	TKKS volume, material balance, logistics costs, availability, and OEE/uptime.
Plant/Garden Division	Conduct biochar application tests, determine doses, monitor soil conditions and productivity.	Test plots, soil data, fertilizer realization, and production response.
Sustainability/ESG	Overseeing MRV, environmental impact, compliance, K3, and ESG reporting.	Emissions data, complaints, audits, and ESG indicators.
Finance & Risk Management	Calculate CBA, ROI, payback, sensitivity analysis, and financing scenarios.	Financial models, risk evaluations, and economic reports.
SDM & TI	Prepare competencies, culture changes, KPI-based incentives, and digital dashboards.	Training, competencies, HR scorecards, and data systems.

Source: Data are processed from the structure of research-related functions and cross-functional implementation needs.

Managerial Implementation Priorities

The final managerial implication is the need for a realistic implementation roadmap. Given that there are risks in the aspects of technology, cost, quality, agronomy, market, and ESG, implementation must be carried out in stages. The roadmap not only sets the time, but also specifies what evidence must be available before the program is expanded.

Table 13 BSC-Based Managerial Implementation Roadmap

Phase	Managerial Focus	Output/Gate Decision
Pra-pilot	PMO determination, location selection, TKKS/fertilizer/cost baseline, vendor due diligence, SOP and MRV design.	Data readiness, technology readiness, and pilot design approval.
Production pilot	Biochar unit operation, yield measurement, OPEX, emissions, batch QC, and material balance.	Initial B/C, biochar quality, availability, and actual production

		costs.
Garden app pilot	Application of biochar on control plots, dose evaluation, soil, nutrient uptake, productivity, and NPK reduction.	Validation of fertilizer savings and no decrease in productivity.
Market validation and ESG	Biochar/by-product market tests, offtaker MoUs, legal reviews, carbon/ESG MRVs, and stakeholder communication.	Offtake/initial sales, verified ESG data, and reduced complaints.
Scale-up bertahap	Replication to other clusters with stage-gate, integration to RKAP, performance contracts, and commercial partnerships.	Increased added value, cost savings, and biomass downstream portfolio.

Source: Data processed as a result of risk analysis, TOWS, and Balanced Scorecard.

Based on these implications, the TKKS biochar strategy will only generate added value if managed as a measurable transformation program. BSC helps ensure that programs not only pursue short-term revenues, but also build the processes, competencies, customer trust, and ESG governance that are prerequisites for program sustainability.

CONCLUSION

Based on the results of the analysis, the development of biochar from empty oil palm bunch waste (TKKS) based on the circular economy at PT Perkebunan Nusantara IV has great strategic potential in increasing the company's added value through optimizing the use of biomass that has not been utilized optimally. The huge potential for the availability of TKKS raw materials supports the development of biochar as part of an integrated biomass downstream program, with a circular economy model that connects the processing process, utilization in the plantation, and product commercialization opportunities. Technically and economically, the development of biochar shows viable prospects, including potential fertilizer cost savings, improved soil quality, as well as the creation of economic value from primary products and by-products. However, successful implementation requires validation through pilot projects, the implementation of strict SOPs and quality control, gradual agronomic testing, and measurable risk management. With the support of the Balanced Scorecard framework, a stage-gate investment approach, and an integrated performance monitoring system, the biochar program can be an important instrument in supporting operational efficiency, environmental sustainability, strengthening ESG aspects, and increasing the competitiveness and added value of PT Perkebunan Nusantara IV in the future.

REFERENCES

Abdul-Hamid, A.-Q., Ali, M. H., Tseng, M.-L., & Hsieh, J. (2022). Industry 4.0 quasi-effect between circular economy and sustainability: Palm oil industry. International Journal of Production Economics, 253, 108616. https://doi.org/10.1016/j.ijpe.2022.108616

Anyaoha, K. E., Zhang, R., Schirrmann, M., & Dransfeld, S. (2022). The use of oil palm empty fruit bunches as a soil amendment to improve growth and yield of crops: A meta-analysis. Agronomy for Sustainable Development, 42(2), 28. https://doi.org/10.1007/s13593-022-00753-z

Bejarano, P. A. C., Rodriguez-Miranda, J. P., Maldonado-Astudillo, R. I., Maldonado-Astudillo, Y. I., & Salazar, R. (2022). Circular economy indicators for the assessment of waste and by-products from the palm oil sector. Processes, 10(5), 903.

https://doi.org/10.3390/pr10050903
Campion, L., Bekchanova, M., Malina, R., & Kuppens, T. (2023). The costs and benefits of biochar production and use: A systematic review. Journal of Cleaner Production, 408, 137189. https://doi.org/10.1016/j.jclepro.2023.137189
El-Naggar, A., Awad, M., Tang, X. Y., Liu, C., Niazi, N. K., Jama, S. M., Tsang, D. C. W., Tack, F. M. G., Ok, Y. S., & Rinklebe, J. (2023). Advances and prospects of biochar in improving soil fertility, biochemical quality, and environmental applications. Frontiers in Environmental Science, 11, 1114752. https://doi.org/10.3389/fenvs.2023.1114752
Harsono, S. S., & Yuliana, D. (2021). Biomass energy from palm oil waste: A sustainable pathway for Indonesia. Renewable and Sustainable Energy Reviews, 143, 110896. https://doi.org/10.1016/j.rser.2021.110896
Hasnain, M., Chen, J., Ahmed, N., Memon, S. A., Naz, M., Ur-Rehman, M., & Li, Y. (2024). Biochar production and characteristics, its impacts on soil health, crop production, and yield enhancement: A review. Plants, 13(2), 166. https://doi.org/10.3390/plants13020166
Jassem, S., Zakaria, Z., & Che Azmi, A. (2022). Sustainability balanced scorecard architecture and environmental performance outcomes: A systematic review. International Journal of Productivity and Performance Management, 71(5), 1728–1752. https://doi.org/10.1108/IJPPM-03-2020-0116
Mio, C., Panfilo, S., & Blundo, B. (2022). Performance measurement tools for sustainable business: A systematic literature review on the sustainability balanced scorecard use. Corporate Social Responsibility and Environmental Management, 29(2), 367–384. https://doi.org/10.1002/csr.2206
Nematian, M., Keske, C., & Ng'ombe, J. N. (2021). A techno-economic analysis of biochar production and the bioeconomy for orchard biomass. Waste Management, 135, 467–477. https://doi.org/10.1016/j.wasman.2021.09.014
Phuang, Z. X., Woon, K. S., Md. Pauzi, N., & Hashim, H. (2022). An integrated life-cycle greenhouse gas protocol accounting on oil palm trunk and empty fruit bunch biofuel production. Waste Management, 154, 13–25. https://doi.org/10.1016/j.wasman.2022.09.026
Purnomo, H., Okarda, B., Dermawan, A., Pacheco, P., Dongol, B. R., & Pham, T. T. (2020). Reconciling oil palm economic development and environmental conservation in Indonesia: A value chain dynamic approach. Forest Policy and Economics, 111, 102089. https://doi.org/10.1016/j.forpol.2020.102089
Rodrigues, L., Hardy, B., Rineau, F., Berner, D., Verheyen, K., & Marhan, S. (2023). The importance of biochar quality and pyrolysis yield for soil carbon sequestration in practice. European Journal of Soil Science, 74(4), e13396. https://doi.org/10.1111/ejss.13396
Sura, P. R., & Ardi, R. (2023). Challenges of circular economy in the palm oil industry: A case from Southeast Asia. Journal of Cleaner Production, 412, 137256. https://doi.org/10.1016/j.jclepro.2023.137256
Supriatna, J., Setiawati, M. R., Sudirja, R., Suherman, C., & Bonneau, X. (2022). Composting for a more sustainable palm oil waste management: A systematic literature review. The Scientific World Journal, 2022, 5073059. https://doi.org/10.1155/2022/5073059

Usapein, P., Tuntiwiwattanapun, N., Polburee, P., Veerakul, P., Seekao, C., & Chavalparit, O. (2022). Transition pathway palm oil research framework toward a bio-circular-green economy model using SWOT analysis: A case study of Thailand. Frontiers in Environmental Science, 10, 877329. https://doi.org/10.3389/fenvs.2022.877329

Wardhani, R., & Rahadian, Y. (2021). Sustainability strategy of Indonesian and Malaysian palm oil industry: A qualitative analysis. Sustainability Accounting, Management and Policy Journal, 12(5), 1077–1107. https://doi.org/10.1108/SAMPJ-07-2020-0259

Xin, X., Guo, L., Nakajima, T., & Sun, C. (2020). Transforming biomass pyrolysis technologies to produce liquid smoke food flavouring. Journal of Cleaner Production, 275, 123096. https://doi.org/10.1016/j.jclepro.2020.123096

Yusoff, S. M., Zulkifli, M., & Ismail, Z. (2021). The drivers of Industry 4.0 in a circular economy: The palm oil industry in Malaysia. Journal of Cleaner Production, 324, 129216. https://doi.org/10.1016/j.jclepro.2021.129216

Zhao, L., Cao, X., Masek, O., & Zimmerman, A. (2022). Heterogeneity of biochar properties as a function of feedstock sources and production temperatures. Journal of Hazardous Materials, 256, 1–9. https://doi.org/10.1016/j.jhazmat.2022.127801