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Value-Based Assessment for Strategic Selection and Optimization of POME Valorization Pathways

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ABSTRACT

Palm oil mill effluent (POME) represents a major environmental burden in the palm oil industry while offering opportunities for resource recovery. This study develops and applies a value-based assessment framework to examine how technological choice influences the integrated environmental–economic performance of POME valorization. Biomethane production and bio-hydrogen production are selected as representative mature and emerging technologies, respectively. Life-cycle environmental performance is quantified using greenhouse gas (GHG) emissions midpoint indicator and natural resources endpoint indicator, reflecting broader environmental damages. A techno-economic assessment is performed to show the economic performance. In addition to conventional return of investment (ROI), the benefits of mitigating environmental impacts are accounted using the return of value (ROV) methodology. The results indicate that the attractiveness of POME valorization pathways depends strongly on how environmental gains are represented. Midpoint-based valuation shows the climate mitigation potential of the biomethane and bio-hydrogen, whereas endpoint-based valuation reveals higher environmental impacts for the energy-intensive hydrogen route, favoring the mature biomethane option in terms of integrated sustainability performance. This contrast demonstrates that technological maturity is reflected not only in cost structure and process stability but also in the balance between avoided impacts and newly introduced environmental burdens. Overall, the proposed value-based assessment framework enables environmental impacts and economic performance to be evaluated on a common value scale, providing a consistent basis for sustainability-oriented decision-making in POME valorization and supporting strategic planning for wastewater management and bio-economy development in the palm oil sector.

Keywords: Life Cycle Assessment, Wastewater valorization, Palm oil mill effluent, Bioenergy pathways, Value-based assessment

INTRODUCTION

The palm oil industry plays a pivotal role in the global vegetable oil market, accounting for approximately 33% of global oils and fats production and nearly 40% of international edible oil trade [1]. However, the large-scale processing of fresh fruit bunches (FFB) into crude palm oil is highly water-intensive, particularly during sterilization and clarification stages, resulting in the generation of substantial quantities of POME. On average, approximately 0.1 tons of effluent per ton of produced crude palm oil is generated as POME. [2]. POME is characterized by high chemical oxygen demand (COD), biological oxygen demand (BOD), oil and grease content, and acidic pH [3]. If inadequately managed, conventional open-pond treatment systems can lead to severe water pollution and significant methane emissions, contributing to climate change [4]. To address these challenges, POME valorization has emerged as an important strategy to transform wastewater from an environmental burden into a valuable resource. Importantly, the POME valorization technologies span a wide range of technology readiness levels (TRLs). On one end, mature technologies have already been deployed at industrial scale, delivering

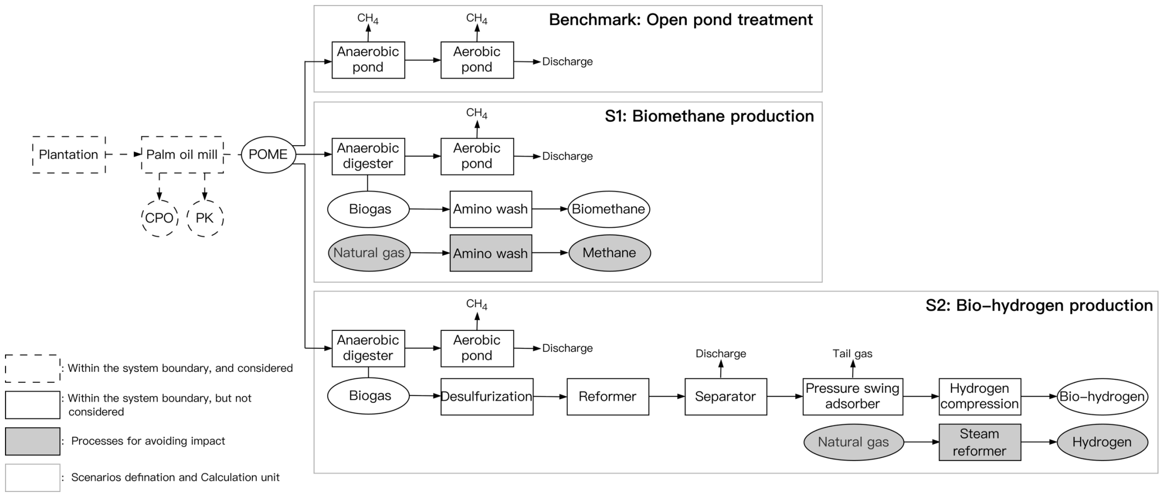

Figure 1: Cradle-to-gate system boundary of POME valorization pathways for benchmark and two valorization

near-term environmental benefits and relatively stable economic returns. On the other end, emerging technologies remain at pilot or laboratory stages, offering potentially higher long-term value but accompanied by greater technical uncertainty, higher costs, and less certain environmental performance. This coexistence of mature and emerging valorization options poses a critical challenge for decision-makers: how to systematically compare technologies with fundamentally different maturity levels on a consistent and transparent basis. Most existing studies evaluate single POME valorization pathways using either environmental indicators, such as life cycle greenhouse gas (GHG) emissions, or economic metrics, such as production cost and profitability, or evaluate these two aspects individually [5, 6]. However, these single-dimensional assessments fail to explicitly integrate environmental impacts with economic performance into a single level to enable holistic comparison across heterogeneous technologies.

This study aims to first characterize the life-cycle performance of POME valorization by examining two representative pathways corresponding to mature and emerging technologies. Building on this characterization, a value-based assessment framework is applied in which environmental impacts are represented in monetary value and added to the economic indicator. The objective is to elucidate how technological choice influences the integrated environmental–economic performance of POME valorization and to provide a quantitative basis for strategic technology selection in sustainable wastewater management and bio-economy development in the palm oil sector.

METHOD

Scenario Design and Settings

To reflect the technological heterogeneity of POME valorization options, this study selects two representative pathways in different levels of technological maturity. Biomethane production via anaerobic digestion is chosen as the mature technology because it has been widely implemented at industrial scale [7] and its relatively stable technical performance and production costs. In contrast, bio-hydrogen production from POME via steam reforming is selected as the emerging technology. Although hydrogen is associated with higher market value and strategic relevance for future low-carbon energy systems [8], this pathway remains at pilot or laboratory scale, leading to higher technical uncertainty and production costs. These two pathways are therefore used as representative cases to examine how differences in technological maturity and value potential influence the integrated environmental–economic performance of POME valorization.

The two scenarios are: S1, POME-to-biomethane with biogas capture and purification, and S2, POME-to-bio-hydrogen via steam reforming. A conventional open-pond treatment without methane removal is used as a benchmark for comparison.

Life Cycle Assessment

This life cycle assessment (LCA) aims to evaluate environmental impact of POME treatment and valorization pathways. The process modeling is based on a mass and energy balance framework, in which each unit operation is represented by literature-based input–output data and linked to corresponding datasets in ecoinvent v3.11. The functional unit (FU) is defined as 1 t of POME utilization. The system boundary is illustrated in **Figure 1** and focuses on POME treatment and down-stream valorization processes. Upstream plantation and palm oil mill (POM) operations are not considered, and POME is considered as the sole feedstock entering the system. The benchmark includes processes of anaerobic and aerobic ponds, and the treated effluent is discharged, while methane generated during treatment is emitted to the atmosphere without removal. In S1, POME is treated by an anaerobic digester (AD) followed by aerobic ponds. The biogas produced from anaerobic digestion is purified through an amino washing process to produce biomethane, which is assumed to substitute fossil-derived methane. In S2, the system boundary is further extended to include biogas desulfurization, steam reforming, gas separation, pressure swing adsorption, and hydrogen compression for bio-hydrogen production. The produced bio-hydrogen is assumed to substitute hydrogen derived from fossil-based methane.

Inventory datas for material, energy and process shown in **Table 1** are primarily derived from literature sources [5, 8]. These data are scaled to the defined FU using proportional coefficients, according to:

$$Flow_{FU} = Flow_{ref} \times \frac{FU}{FU_{ref}} \quad (1)$$

where $Flow_{FU}$is the inventory flow per FU, and $Flow_{ref}$ is the reference flow reported in the literature for a given FU FU_{ref}. All inventory flows are scaled linearly to the functional unit based on reported reference data, assuming steady-state operation and constant conversion efficiencies.

For the benchmark, the generated biogas is considered as direct emissions. For S1, inventory data include water and electricity input, and the purification process. A biomethane purification efficiency of 97% is assumed, while the remaining fraction is released as losses and accounted for in the emission calculation. For S2, additional material and energy inputs include monoethanolamine (MEA) for gas treatment and metal oxides (iron oxide, copper oxide, and nickel) as catalysts for reforming and downstream conversion. In this study, catalyst recovery and re-use are not considered. Steam consumption includes low-, medium-, and high-pressure steam, which are represented by an average energy intensity of 2.80 MJ/kg steam to calculate both steam demand and its associated environmental impacts. Tail gas is also generated from the pressure swing adsorption unit. The composition consists of 94.66 % CO_2, 2.00 % H_2S, 1.25 % water, 0.93 % NH_3, 0.40 % CH_4, 0.40 % C_2H_7NO, 0.21 % H_2, 0.11 % $C_{13}H_{25}O_7N_3S$, and 0.04 % CO [8]. It is assumed to be directly released, and only CO_2 (587 kg) and CH_4 (2.48 kg) are included in the GHGs calculation. Wastewater and digestate from two valorization pathways are estimated based on mass balance. For the fossil-derived alternatives, cradle-to-gate environmental impacts are adopted from ecoinvent v3.11 database, which includes natural gas production, amine washing, and steam reforming.

Table 1: Inventory data of each scenario.

S1	**Material/Energy**	**Unit**	**Value**
Input	POME	t	1
	Water	m^3	0.01
	Electricity	kWh	0.03
	Biogas-to-biomethane purification (amine washing)	m^3	20.79
Output	Biomethane	m^3	20.17
	Digestate	t	0.11
	Wastewater	t	0.89
S2			
Input	POME	t	1
	Monoethanolamine	kg	0.03
	Iron oxide	kg	0.05
	Copper oxide	kg	0.08
	Nickel	kg	0.06
	Water	kg	17.50
	Steam	kg	570.43
	Heat	MJ	1693.50
Output	Hydrogen	kg	6.08
	Tail gas	kg	620.21
	Wastewater	t	0.59

Direct methane emissions from each stage are obtained by multiplying the corresponding treatment organic load by the emission factors for facultative and other treatment and for discharge to the water environment [4]. Chemical oxygen demand concentrations [5, 9] are assumed at three treatment stages: from palm oil mill to anaerobic digesters, from anaerobic digesters to aerobic digesters, and from aerobic digesters to final discharge. For the benchmark, where methane is not recovered, biogas produced in the anaerobic stage is assumed to be directly released to the atmosphere. Therefore, total methane emissions are calculated as the sum of emissions from all three treatment stages, resulting in 14.2 kg CH_4 per FU and representing a major source of GHG emissions. For S1, methane generated in the anaerobic stage is assumed to be captured as biogas. Direct emissions in S1 include those from the aerobic stages and the residual biogas released during purification, which is assumed to be 3% of the produced biogas, resulting in 1.7 kg CH_4. For S2, direct emissions include methane released during the mill-to-anaerobic digester stage and emissions associated with tail gas from hydrogen production. It is assumed that, apart from the above, no methane is released from other processes.

Two impact assessment methods are applied based on the ReCiPe 2016 framework. First, the ReCiPe 2016 midpoint (H) method is used with a focus on global warming potential (GWP100), expressed as kg CO_2-eq, to quantify the climate change impact associated with POME treatment and conversion. Second, the ReCiPe 2016 endpoint (H) method is applied with a focus on the Natural Resources damage category, expressed in monetary units (USD), to represent resource depletion impacts. Background inventory data are all taken from ecoinvent 3.11, using datasets representative of Malaysia, one of the major palm oil–producing countries. These two results are subsequently used as two alternative representations of environmental gain in the value-based assessment, providing complementary perspectives on climate-related and resource-related impacts.

Techno-economic assessment

Techno-economic assessment (TEA) is performed, which parameters are shown in **Table 2**. Production costs consist of capital costs and operating costs. Capital costs are annualized directly based on resource data [8, 10]. It should be noted that the techno-economic parameters differ significantly between the two pathways due to their different technology maturity levels. The objective of this study is not to normalize these differences, but to evaluate their influence on integrated environmental–economic performance under consistent functional unit and system boundary assumptions.

Table 2: Techno-economic analysis assumptions.

	Economic parameters	Unit	Value
S1	Lifetime	Year	15
	Annualized factor		0.096
	Input/output rate		0.65
	Total CAPEX	USD	155000
	Annual operating time	h/year	4380
	Annual OPEX	USD/year	25600
	Water selling price	USD/t	0.79
	Electricity selling price	USD/kWh	0.09
	Biomethane selling price	USD/m^3	0.55
S2	H_2 production	t/year	963.34
	Lifetime	Year	20
	Annualized factor		0.1
	Hydrogen output	kg	6.08
	Total CAPEX	USD	121080920
	Annual OPEX	USD/year	52717984.74
	Hydrogen selling price	USD/kg	19.68

The annualized capital cost is calculated as:

$$Annualized\ CAPEX = CAPEX_{tot} \times AF \tag{2}$$

where $CAPEX_{tot}$ is the total capital cost of the plant, and AF is the annualized capital cost factor derived from the plant lifetime.

For S1, the capital cost allocated to the FU is then obtained based on the annual operating time and the output or input rate of the system:

$$CAPEX_{FU-S1} = \frac{Annualized\ CAPEX}{R \times t_{op}} \tag{3}$$

where $CAPEX_{FU-S1}$ is the capital cost per FU for S1, R is the output rate of the system (per hour), and t_{op} is the annual operating time (h·yr^{-1}).

For S2, the capital cost allocated to the FU is based on annual hydrogen production and hydrogen production per FU:

$$CAPEX_{FU-S2} = \frac{Annualized\ CAPEX \times\ H_2\ output}{Annual\ H_2\ production} \tag{4}$$

where $CAPEX_{FU-S2}$ is the capital cost per FU for S2, $H_2\ output$ is amount of hydrogen produced per FU, and $Annual\ H_2\ production$ is annual production of hydrogen.

For S1, operating costs are calculated based on the annual operating cost and the cost of input materials per FU:

$$OPEX_{FU-S1} = \frac{OPEX_{ann}}{R \times t_{op}} + \sum(Input_i \times Price_i) \tag{5}$$

where $OPEX_{FU}$ is the operating cost per FU, $OPEX_{ann}$ is the annual operating cost provided in the resource data, R is the output rate of the system (per hour), and t_{op} is the annual operating time (h·yr^{-1}). $Input_i$ is the quantity of input i required per FU, and $Price_i$ is the corresponding unit price.

For S2, operating costs are calculated based on the annual operating cost, annual hydrogen production and hydrogen production per FU:

$$OPEX_{FU-S2} = \frac{Annualized\ OPEX \times\ H_2\ output}{Annual\ H_2\ production} \tag{6}$$

where $OPEX_{FU-S2}$ is the operating cost per FU for S2, $H_2\ output$ is amount of hydrogen produced per FU, and $Annual\ H_2\ production$ is annual production of hydrogen. And cost of input materials and energy in S2 are included in $OPEX_{ann}$.

Product revenues are calculated as the market values of POME-derived products:

$$Total\ revenue = \sum(Product_j \times Price_j) \tag{7}$$

where $Product_j$ is the output quantity of product j per FU, and $Price_j$ is the corresponding market price.

The net economic value (NEV) is evaluated by subtracting total revenues (TR) with the sum of capital and operating costs per FU.

The benchmark is not included in the cost calculation, because this study focuses exclusively on the costs associated with valorizing an existing POME treatment facility.

Value-based assessment

Unlike conventional investment analysis that considers only ROI, value-based assessment also incorporates environmental gains to represent the sustainability value of impact mitigation in a unified metric.

Firstly, the return of investment (ROI) is used to evaluate the conventional economic performance of each scenario. ROI is defined as:

$$ROI = \frac{Financial\ gain - Financial\ loss}{Total\ investment}$$

where $Financial\ gain$ represents the revenue obtained from product sales and $Financial\ loss$ includes capital and operating costs.

ROI is applied to quantify the economic attractiveness of each pathway without considering environmental externalities and serves as a reference to the integrated sustainability performance indicated by ROV.

The integrated sustainability performance is quantified using the ROV [11]:

$$ROV = \frac{Value\ gain - Value\ loss}{Total\ investment} \quad (8)$$

where $Value\ gain$ includes both financial and environmental gains from investment, while $Value\ loss$ represents the total cost, including both $CAPEX$ and $OPEX$.

Two approaches are applied to quantify environmental gains. Under the midpoint-based approach, environmental gain is estimated by multiplying the avoided GHG emissions by the projected Malaysian carbon price:

$$Eniviromental\ gain_{GHG} = \Delta GHG \times P_{carbon} \quad (9)$$

where $\Delta GHG$is the reduction from benchmark and including the avoided fossil-derived products in GWP100 and $P_{carbon}$is the carbon price (RM 35–45/t CO_2-eq) [12], we use the average 40 RM/t CO_2-eq, or 10 USD/t CO_2-eq.

Under the endpoint approach, environmental gain directly uses the Natural Resources damage category expressed in monetary units (USD). This value is derived from the ReCiPe2016 endpoint (H) method, which converts resource depletion into economic terms based on the marginal increase in future extraction costs caused by current resource use, thereby representing the damage to natural capital in value units.

The economic gain is calculated as NEV from product sales, while total investment includes $OPEX_{FU}$ and $CAPEX_{FU}$. The ROV indicator therefore integrates economic profitability and environmental externalities into a unified value metric, enabling direct comparison between POME valorization technologies.

RESULTS AND DISCUSSION

The environmental impacts of the two scenarios are evaluated using two complementary approaches. **Figure 2a** presents the GHG emission results, with the conventional treatment used as a benchmark. Both S1 and S2 achieve net GHG reductions, which are 392.57 and 158.99 kg CO_2-eq, respectively. This indicates that diverting POME from direct discharge to valorization pathways can substantially mitigate climate impacts. For S1, the dominant contribution is the avoided GHG emissions associated with fossil-derived energy substitution through biomethane utilization, totally 447.38 kg CO_2-eq. This negative contribution outweighs the positive emissions arising from electricity use, biogas purification, and material inputs, resulting in a net GHG reduction. Direct methane emissions are relatively low because methane generated in the anaerobic stage is assumed to be captured and upgraded, with only minor losses during purification. In S2, avoided GHG emissions is 513.97 kg CO_2-eq, but this benefit is partially offset by process emissions. Steam and heat consumption for reforming and gas separation represent the largest positive contributors, followed by tail gas release. As a result, although S2 still achieves net GHG reduction compared with the benchmark, its total GHG benefit is smaller than that of S1. Overall, the GHG results highlight contrasting mitigation mechanisms: S1 mainly reduces emissions through methane capture and fossil energy substitution, whereas in S2 the avoided emissions from hydrogen substitution are largely offset by substantial process emissions. Therefore, biomethane is more effective than bio-hydrogen in reducing GHG emissions under current conditions.

Figure 2b shows the endpoint results for natural resources in terms of avoided damage, incurred damage, and net damage for the two valorization scenarios. For S1, the net damage is -6.17 USD, showing that the avoided damage associated with fossil-derived substitution exceeds the resource damage generated during processing. This result indicates that biomethane production provides a small net benefit in the natural resources indicator, as the resource savings from displaced fossil energy outweigh the additional resource use required for treatment and purification. In S1, the avoided damage associated with fossil-derived energy substitution slightly exceeds the resource damage generated during processing, resulting in a small negative net damage. This indicates that biomethane production leads to a marginal net benefit in the natural resources category, as the resource savings from displaced fossil energy offset the additional resource use required for treatment and upgrading. In contrast, the net damage of S2 is 12.41 USD, exhibiting a positive net damage. Although hydrogen substitution leads to a larger avoided damage than in S1, this benefit is more than offset by the substantial resource damage

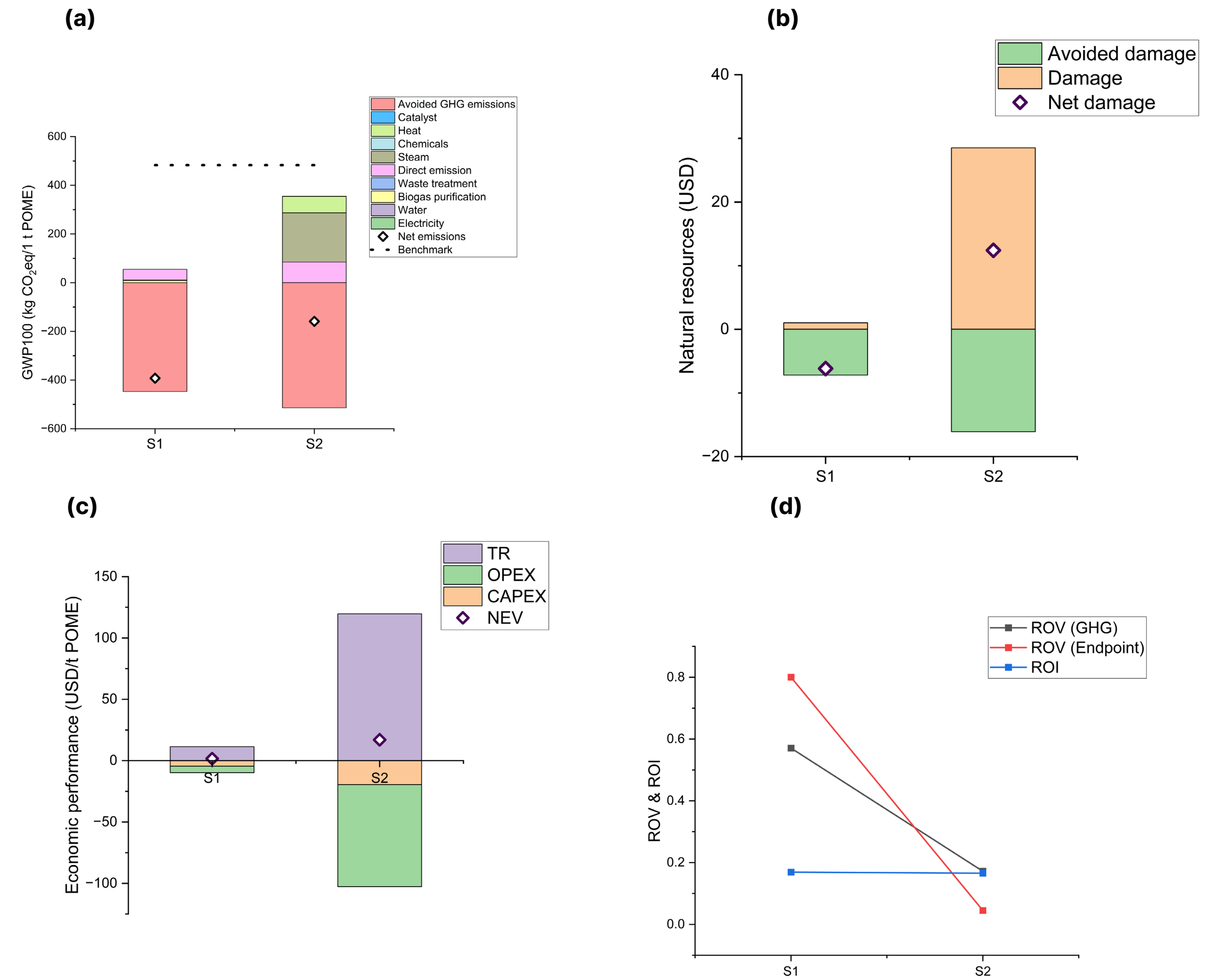

Figure 2. Integrated results of POME management scenarios (B–S2): (2a) GHG emissions (GWP100), (2b) endpoint indicator (Natural resources), (2c) economic performance (CAPEX, OPEX, TR, and NEV), and (2d) ROV based on GHG- and endpoint-derived environmental gains and financial gains and ROI only based on financial gains.

caused by conversion processes. Steam contributes significantly to the positive damage term. As a result, S2 shows an overall increase in natural resource impacts.

Overall, the environmental assessment indicates that biomethane production delivers more favorable environmental performance because the bio-hydrogen production is much more energy-intensive.

Figure 2c illustrates the economic performance of the two valorization scenarios in terms of capital expenditure (CAPEX), operating expenditure (OPEX), TR, and NEV. In S1, both CAPEX and OPEX are relatively low, reflecting the technological maturity of the biomethane pathway and its moderate energy and material requirements. The resulting TR from biomethane production slightly exceeds the total production cost, leading to a relatively low NEV. This indicates that biomethane production can approximately balance costs and revenues under the assumed conditions. In contrast, S2 exhibits substantially higher production costs, particularly in OPEX, which is mainly driven by intensive steam, heat, and chemical inputs required for hydrogen production. Although S2 achieves a much higher TR due to the higher market value of hydrogen, this revenue is largely offset by the elevated operating costs. As a result, the NEV of S2 remains positive but is only moderately higher than that of S1. Overall, the economic results suggest that S1 represents a low-risk and cost-stable option, whereas S2 offers higher revenue potential at the expense of significantly increased cost intensity.

Figure 2d compares the performance of the two valorization scenarios using ROI and ROV. In terms of conventional ROI, both scenarios exhibit similar profitability, with ROI values of 17% for S1 and 18% for S2. This indicates that biomethane and bio-hydrogen pathways provide comparable financial returns under the assumed market and cost conditions. When environmental gains are incorporated using the midpoint impact approach (GHG-only), a clear differentiation emerges. The ROV_{GHG} of S1 reaches 0.57, substantially higher than the value of 0.17 obtained for S2. This result reflects the stronger climate mitigation effect of biomethane production through effective methane capture and fossil energy substitution, whereas the larger process-related emissions in S2 reduce its net GHG-based value gain. A larger contrast is observed when environmental gains are evaluated using the endpoint-based approach. The $ROV_{endpoint}$ of S1 reaches 0.8, while that of S2 drops to 0.04. This indicates that, once broader environmental damage categories are considered, the integrated sustainability performance of biomethane production is markedly superior to that of bio-hydrogen production. The intensive energy and material requirements of the hydrogen pathway substantially increase its endpoint damages, which are not fully compensated by its higher economic return. Overall, the value-based assessment demonstrates that scenario ranking is highly sensitive to how environmental gains are represented, with S1 consistently favored when both climate-related and damage-oriented indicators are considered.

CONCLUSIONS

This study applied a value-based assessment framework to examine how technological choice influences the integrated environmental–economic performance of POME valorization. By selecting biomethane production and bio-hydrogen production as representative mature and emerging technologies, the analysis first characterized their life-cycle environmental and economic profiles and then integrated these dimensions using the ROV.

The ROV results demonstrate that the attractiveness of POME valorization pathways depends strongly on how environmental gains are represented. When environmental performance is expressed through midpoint indicators focusing on GHG emissions, the bio-hydrogen pathway can appear competitive due to its high product value and credited climate benefits. In contrast, when endpoint indicator is applied to capture a broader environmental burden on natural resources, the biomethane pathway shows a superior integrated performance. This difference indicates that technological maturity is reflected not only in process reliability and cost structure, but also in the balance between avoided impacts and newly introduced environmental burdens. From a methodological perspective, value-based assessment offers a means to integrate LCA and TEA by expressing environmental impacts in value terms, but its interpretation is constrained by the assumptions underlying environmental valuation. GHG-based valuation depends on carbon price scenarios that presuppose the existence of policy instruments such as carbon taxes or markets, while endpoint-based resource valuation reflects theoretical damage costs rather than actual economic transactions. Several limitations should be acknowledged. In the economic assessment, labor employment and associated wage costs were not explicitly considered, which may lead to an underestimation of total production costs. In addition, catalyst recovery and reuse were not included, and tail gas was assumed to be directly emitted, which may overestimate environmental burdens for advanced configurations.

Overall, the proposed framework provides a quantitative basis for comparing mature and emerging POME valorization technologies on a common value scale. It supports strategic technology selection by revealing how technological maturity shapes integrated sustainability performance and offers a structured approach for guiding sustainable wastewater management and bio-economy development in the palm oil sector.

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