

Article

Integrated Techno-Economic, Environmental Screening, and Social Return on Investment Analysis of Community-Scale Sawdust–Polypropylene Co-Pyrolysis for Heavy-Metal Adsorbent Production in Rural Area, Thailand

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Abstract

The co-pyrolysis of waste sawdust and non-recyclable polypropylene at 500 °C was investigated for low-cost adsorbent production and solid waste valorization in rural Thailand. Sustainability was evaluated through techno-economic analysis, gate-to-gate environmental screening, CO₂ emission accounting, adsorption cost analysis, and social return on investment assessment. The sawdust–polypropylene biochar produced at 500 °C production system requires a total capital expenditure of 46,000 THB and achieves a unit production cost of 316 THB kg^{−1} at a 35% *w/w* biochar yield, 7–14 times lower than commercial granular-activated carbon and powdered-activated carbon. Based on a hypothetical community-scale deployment scenario, the estimated capital expenditure payback period under in-house granular-activated carbon substitution falls below six months. All annual techno-economic and SROI results presented in this study represent scenario-based screening estimates and should not be interpreted as demonstrated community-scale performance. Gate-to-gate environmental screening estimated gross production emissions of 8.771 kg CO₂e kg^{−1} SPB-500. A consequential waste-diversion scenario incorporating carbon sequestration and avoided-disposal credits yielded a hybrid scenario-based net greenhouse-gas balance of +3.082 kg CO₂e kg^{−1} SPB-500, supporting its potential application under the evaluated scenario of approximately 0.4–5.9 kg CO₂e kg^{−1} relative to commercial-activated carbon benchmarks. Social return on investment analysis yields a base-case ratio of 1.39:1 (five-year total present value: 6,025,841 THB; minimum across sensitivity scenarios: 1.13:1), with water quality improvement (SDG 6; 46.1%) and health risk reduction (20.7%) jointly accounting for 66.8% of monetized outcomes, confirming investment justification from public health benefits alone. Quantifiable alignment is demonstrated across five UN Sustainable Development Goals. Collectively, these findings suggest that SPB-500 co-pyrolysis has the potential to be an economically accessible and socially beneficial waste-valorization technology under the evaluated scenario, supporting its potential application in decentralized heavy-metal remediation in resource-constrained communities.



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Keywords: co-pyrolysis; sawdust; polypropylene; biochar; techno-economic analysis; environmental screening assessment; scenario-based greenhouse-gas assessment; SROI

1. Introduction

Global plastic production has exceeded 400 million tons per year, with polypropylene (PP) constituting approximately 20% of total output as one of the most widely consumed thermoplastics in packaging, consumer goods, and industrial applications [1,2]. Despite its prevalence, a substantial proportion of post-consumer PP waste falls outside formal recycling infrastructure, particularly in low- and middle-income countries, where inadequate collection systems result in open dumping, uncontrolled burning, and landfill disposal [3]. Such practices result in continuous soil and water pollution, release particulates, and direct emissions of greenhouse gases, which together impose negative health impacts on communities and act as a source of climate forcing [4,5]. This concern about the PP waste problem, both its scale and longevity, has led to greater efforts to explore thermochemical routes of valorization that both mitigate the waste and produce economically useful products.

Sawdust is one such lignocellulosic byproduct made up mainly of cellulose, hemicellulose, and lignin that serves as an additional yet challenging waste stream in wood-based processing industries [2,6]. As witnessed in rural and peri-urban parts of Southeast Asia, and particularly within the Chaiyaphum province of Thailand analyzed in this study, sawdust waste is produced in large volumes in both sawmills and furniture factories, which dispose of this waste through unregulated incineration due to lack of proper collection and energy recovery systems. The use of sawdust as a complement to PP wastes within a thermally driven process thus becomes highly strategic [7,8].

Pyrolysis, the thermal decomposition of carbonaceous feedstocks in the absence of oxygen at temperatures typically ranging from 300 to 700 °C, produces three principal co-products: biochar (a carbon-rich solid), bio-oil (a condensable liquid), and syngas (a non-condensable combustible gas) [9,10]. Co-pyrolysis of lignocellulosic biomass and plastic waste has attracted increasing research attention owing to reported thermochemical synergies during thermal degradation: hydrogen-rich volatile compounds released during PP decomposition enhance bio-oil quality and yield, whilst the lignocellulosic matrix of sawdust promotes stable carbonaceous biochar formation through its inherently high oxygen-to-carbon ratio and solid-phase carbon-retention capacity [8,11,12]. These synergistic interactions, combined with the inherent feedstock flexibility of batch pyrolysis systems, render co-pyrolysis a technically promising route for integrated waste valorization at community scale [7,13].

Recent work by Jena, M.K. et al. (2026) further demonstrated the potential of biomass–plastic co-pyrolysis for sustainable carbonaceous material production and highlighted the need for integrated sustainability assessments beyond process performance alone [14]. Notwithstanding the growing experimental literature on biomass–plastic co-pyrolysis, rigorous process-level techno-economic analyses (TEAs) remain comparatively scarce, particularly for small- and community-scale systems intended for deployment in resource-constrained settings [15,16]. The majority of published TEA studies address large-scale centralized facilities that require substantial capital investment and well-developed feedstock logistics conditions that may not be achievable in rural or peri-urban communities with limited technical and financial capacity [17,18]. Fuel choice is an important issue during design as it influences the operating cost, greenhouse-gas emission, efficiency of energy conversion, control ability of the process, and local infrastructure. However, most community-scale research considers only one type of heating and provides insufficient

information about the sustainability of a specific combination of fuels. This research evaluates the performance of an LPG-operated pyrolysis system as an example of a simple and easy-to-apply combination of fuels in rural Thailand [19,20]. This gap constitutes a material barrier to evidence-based technology deployment at the community scale.

In this research, we aim to perform a concise sustainability screening on an LPG-powered community-level system for pyrolyzing sawdust and polypropylene to produce SPB-500 adsorbent in Thailand's rural areas. Although a plethora of research work on biomass-plastic co-polymerization is available, previous studies mainly focused on pyrolytic behavior, product yields, physiochemical properties, and the adsorbent efficacy of produced biochar. More recent works have also shed more light on the mechanisms of co-polymerization and product valorization process. However, studies that assess economic viability, environmental implications, GHG emissions, and the social impacts of such systems simultaneously are scarce, especially for small-scale, community-based implementations in developing countries [21,22]. In this context, the uniqueness of this current study is the combined use of techno-economic analysis (TEA), environmental assessment, GHG emission accounting, adsorption cost assessment, and Social return on investment (SROI) analysis to conduct an overall sustainability analysis of SPB-500 production [15,16,19,20,23,24].

The goals for this research are as follows: (1) to analyze production viability, capital costs, operating costs, per-unit cost of production, and payback period of SPB-500 production at a community scale, powered by LPG; (2) to determine gross production emissions and estimate net greenhouse-gas balance using gate-to-gate CO₂ screening approach, which includes production emissions, carbon neutrality assumptions, and avoided emissions due to waste reduction; (3) to compare selected environmental impacts associated with SPB-500 production against those of commercial-grade adsorbents using screening metrics such as GWP100, cumulative energy demand, and factors of eutrophication/toxicity; and (4) to measure the social, environmental, and financial benefits of utilizing SPB-500 using scenario-based Social return on investment analysis. Previous experimental work demonstrated that SPB-500 exhibited excellent Cu²⁺ adsorption performance, including a maximum adsorption capacity of 126.1 mg g⁻¹, rapid equilibrium, favorable Freundlich isotherm behavior, pseudo-second-order kinetics, and good regeneration stability. These experimentally validated adsorption results provide the technical basis for the production scenario, wastewater treatment capacity, and sustainability assessment (TEA, environmental assessment, and SROI) presented in this study [25].

2. Materials and Methods

In this study, the adsorption effectiveness of SPB-500, including adsorption isotherms, kinetics, thermodynamics, pH effects, regeneration performance, and Cu²⁺ removal efficiency, has been comprehensively investigated in our previous study and is therefore not repeated here. The present work builds upon those experimentally validated adsorption results and focuses on the techno-economic, environmental screening, and SROI assessment of SPB-500 production and implementation [25,26]. The current research, however, focuses more on the sustainability issues that will arise from producing and utilizing SPB-500 technology in a community-level setting. The pyrolysis system processes (Figure 1) a mixed feedstock composed of sawdust and non-recyclable post-consumer polypropylene (PP) plastic waste at a weight ratio of 4:1, corresponding to a total daily feed input of 1 kg (800 g of sawdust and 200 g of PP waste). The pyrolysis reactor is operated under uniform conditions at a fixed temperature of 500 °C, which has been identified as suitable for producing high-quality biochar. All experimental, economic, and environmental assessments in this study were based exclusively on the LPG-fired configuration used

during reactor operation; alternative heating fuels were not evaluated. The mass ratio of sawdust to polypropylene was established as 4:1 (*w/w*) based on synergy effects reported in the literature when pyrolyzing these waste materials together, as well as their availability in the geographical region where the experiment took place. Sawdust was used as a dominant feedstock to produce maximum biochar, whereas the purpose of including hydrogen-containing polypropylene was to enhance the carbonization process of sawdust. The pyrolysis temperature of 500 °C was selected considering previous works that have revealed better surface area, porosity, carbon, and adsorption abilities when compared to lower temperatures. Therefore, the aforementioned conditions were chosen considering the literature findings, the availability of feedstocks, and the desired characteristics of SPB-500.

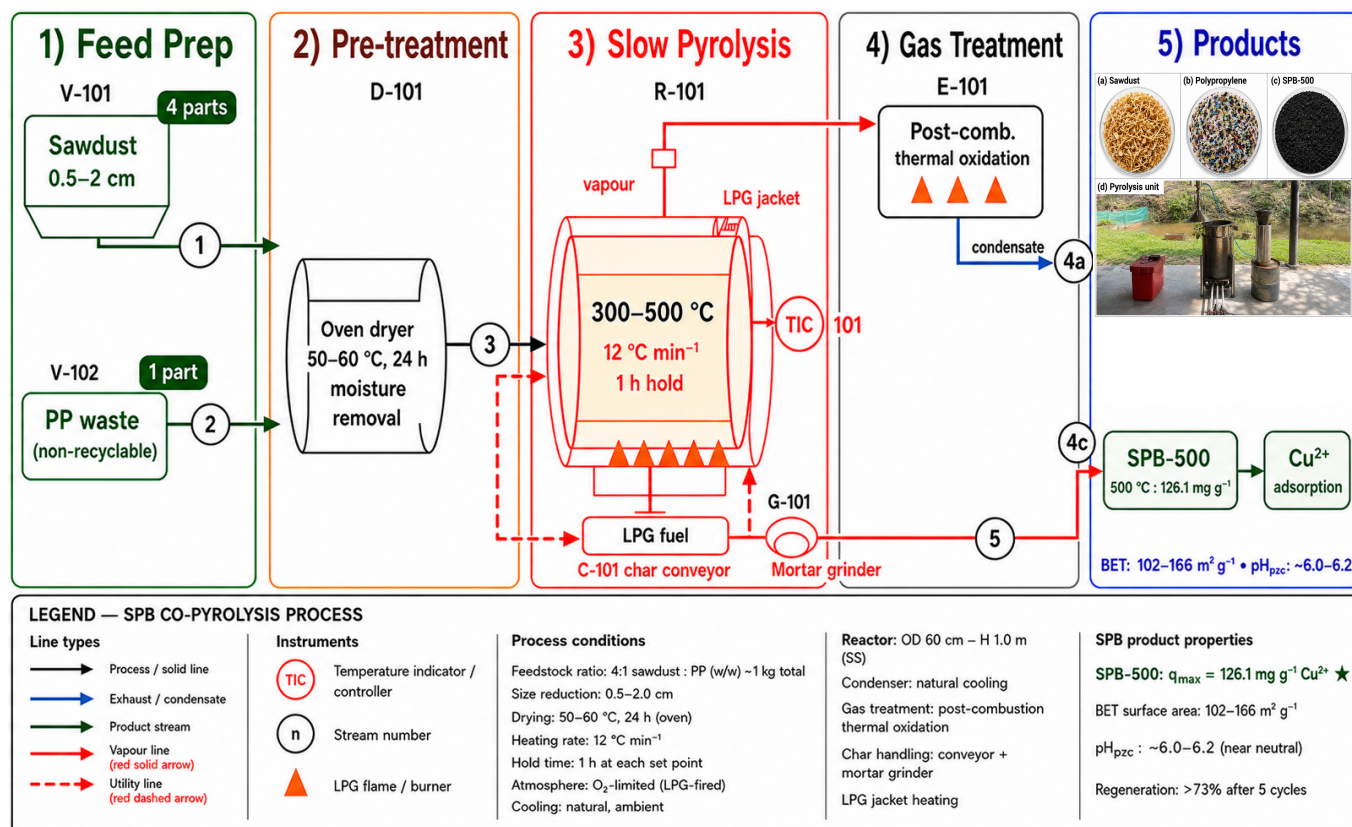


Figure 1. Co-pyrolysis system processes for SPB adsorbent production; (a) sawdust feedstock (S/W). (b) Polypropylene (PP) waste feedstock, (c) SPB-500 biochar adsorbent produced at 500 °C and (d) community-scale LPG-fired co-pyrolysis reactor. ★ = scenario-based greenhouse-gas assessment under waste valorisation conditions. FEP and HTP are qualitative literature-based benchmarking indicators and do not represent quantified midpoint LCIA results.

This projection of a production capacity of 1200 kg SPB-500 yr⁻¹ from the techno-economic analysis is a representation of a simplified economic scaling study and cannot be assumed as the proven production capacity of the reactor tested at a laboratory scale within this study. The feasibility analysis for reactor capacity, batch time cycle, drying capacity, labor capacity, equipment utilization, maintenance, and other parameters was outside the purview of this project. Therefore, the production capacity projected here needs to be taken as a tentative figure and confirmed by actual pilot-scale studies in the future.

2.1. Economic Analysis of SPB Production

An economic analysis was conducted to evaluate the production cost of the sawdust–polypropylene biochar (SPB) adsorbent and to benchmark its cost-effectiveness against commercially available adsorbents for heavy-metal removal. The analysis encompassed capital expenditure (CAPEX) for reactor fabrication, operating expenditure (OPEX) per production batch, and a simplified payback assessment at modest scale-up. All cost estimates are expressed in Thai Baht (THB) and United States Dollars (USD), using a reference exchange rate of 35.8 THB per USD (Bank of Thailand current rate 2024 average).

2.1.1. Capital Expenditure (CAPEX)

The capital cost of the SPB production system was estimated based on the locally fabricated but nevertheless continuous locally fabricated batch slow pyrolysis reactor described in Section 2.1. The reactor was designed as a laboratory-scale prototype for experimental validation and economic screening rather than as a fully engineered commercial system. Therefore, engineering parameters such as maximum reactor loading, effective working volume, batch cycle duration, daily throughput, burner efficiency, heat duty, and heat losses were beyond the scope of the present study and should be established through future pilot-scale engineering design and validation. The total estimated CAPEX is summarized in Table 1.

Table 1. CAPEX for the locally fabricated SPB co-pyrolysis production system.

Equipment Item	Specification	Cost (THB)	Cost (USD)
Stainless-steel reactor (R-101)	OD 60 cm, H 1.0 m, locally fabricated	25,000	699
LPG burner and gas fittings	Industrial grade, 15–20 kW	4500	126
Temperature controller (TIC-101)	PID type, K-type thermocouple	2500	70
Char screw conveyor (C-101)	Manual/semi-automatic, stainless steel	3000	84
Drying oven (D-101)	50–100 °C, 50 L capacity	8000	223
Ancillary items (piping, safety, insulation)	Valves, gauges, fittings	3000	84
Total CAPEX		46,000	1286

Note: Skilled labor: approximately 500 THB h^{−1}. The reactor size values mentioned above refer only to the physical prototype used for testing purposes and cannot be used as proof of the reactor’s commercial design validation. Selection of a reactor load of 1 kg as a test operational variable did not imply that such a value necessarily represented the maximal reactor’s loading potential. Neither technical nor economical parameters, such as the effective working volume, thermal efficiency of the system, heat loads, cycle time analysis, equipment utilization, manufacturing schedule, and maintenance needs have been analyzed in this experiment.

2.1.2. Operating Expenditure (OPEX) per Production Batch

The operating cost per batch was estimated based on the actual experimental conditions reported of 1 kg total feedstock (800 g sawdust and 200 g PP waste, 4:1 *w/w*), oven drying at 50–60 °C for 24 h, slow pyrolysis under LPG-fired heating at 12 °C min^{−1} to 300–500 °C with a 1 h hold period at each target temperature, followed by natural cooling. The resulting batch OPEX and cost per kilogram of SPB produced are presented in Table 2.

Table 2. OPEX per production batch and cost per kilogram of SPB-500 produced.

Cost Item	Quantity Per Batch	Unit Cost (THB)	Batch Cost (THB)	Batch Cost (USD)
Sawdust feedstock (V-101)	800 g	0.5 per kg	0.4	0.01
PP plastic waste feedstock (V-102)	200 g	2.0 per kg	0.4	0.01
LPG fuel (R-101 burner)	~0.4 kg LPG	20.0 per kg	8	0.22
Electricity for oven drying (D-101)	1.5 kWh	4.5 per kWh	6.75	0.19
Labor—grinding and handling (G-101)	1 h	80 per h	80	2.23
Maintenance and depreciation allowance	Per batch	—	15	0.42
Total batch OPEX	—	—	110.55	3.09
Estimated SPB yield at 500 °C (~35% <i>w/w</i>) [27]	350 g per batch	—	—	—
Production cost per kg SPB-500	—	—	316 THB kg ^{−1}	~8.8 USD kg ^{−1}

2.1.3. Simplified Payback Analysis

A simplified payback analysis was performed for a community-scale production case with an annual SPB-500 production rate of 1200 kg year^{−1} (100 kg month^{−1}). This analysis was done using the experimental cost of SPB-500 production per-unit weight as described in Table 2 (316 THB kg^{−1} SPB-500) and resulted in an annual operational expenditure (OPEX) estimate of 379,200 THB year^{−1}. Using a relatively conservative price of 40 USD kg^{−1} (~1432 THB kg^{−1}), the annual revenue from production of SPB-500 was estimated to be about 1,718,400 THB year^{−1}. This leads to an annual net operating profit of ~1,339,200 THB year^{−1} after accounting for the operational cost. Capital investment expenditure (CAPEX) necessary for the locally constructed SPB-500 production system was assumed at 46,000 THB (1286 USD). With this set of parameters, the simple payback period could be estimated through

$$\text{Annual OPEX} = \text{Unit production cost} \times \text{Annual production capacity}$$

$$\text{Annual revenue} = \text{Selling price} \times \text{Annual production capacity}$$

$$\text{Annual operating surplus} = \text{Annual revenue} - \text{Annual OPEX}$$

$$\text{Payback period} = \text{CAPEX} / \text{Annual net operating surplus}$$

It resulted in a payback period of ~0.034 year (≈0.4 months). This good performance can be largely credited to the use of waste materials in the SPB-500 synthesis as a low-cost raw material feedstock, low equipment investment compared to commercial GAC production facilities, and lack of any chemical treatments during the processing. Also, the estimated production cost of SPB-500 appears significantly lower than the current market prices of both commercial GAC and PAC. The comparison carried out in this paper regarding commercial GAC and PAC is mainly based on factors including production cost, price in the market, and environmentally related screening parameters. This does not imply that the two can be considered as substitutes to each other based on performance equivalence because there could be great variability in adsorption capacities, breakthrough characteristics, regeneration efficiency, life cycle, and performance in water treatment. An evaluation based on function units like cost or environment per pound of pollutant eliminated would be a better choice in future studies. It must be pointed out, however, that the above payback analysis constitutes only a preliminary screening-level economic evaluation made with respect to the current laboratory-scale production data and a hypothetical annual production volume. A detailed engineering-economic evaluation with consideration

of reactor utilization and batching scheduling, labor efficiency and maintenance cost, raw material sourcing and equipment availability, process scale-up, etc., is recommended prior to commercial implementation.

2.2. Simplified Environmental Screening Assessment of SPB Production

2.2.1. Goal and Scope Definition

The goal of this environmental screening assessment is to evaluate the environmental performance of the SPB co-pyrolysis production system relative to commercially produced activated carbon using selected environmental indicators and literature-based benchmarking. The scope is gate-to-gate (as shown in Table 3), spanning from the point of feedstock receipt at the production site to the point of finished SPB adsorbent ready for use. End-of-life (EOL) stages including spent adsorbent regeneration and disposal and upstream background processes (feedstock cultivation, transportation to site) are excluded from the system boundary in this screening assessment, as site-specific inventory data for these stages were not available.

Table 3. System boundary definition for the SPB gate-to-gate environmental screening assessment.

Stage	Included in System Boundary	Excluded/Rationale
Feedstock acquisition	Receipt of sawdust and PP waste at production site	Upstream collection and transport: excluded waste-input allocation (ISO 14044) [28]
Pre-treatment (drying, size reduction)	Electricity for oven drying (D-101); manual size reduction	Equipment manufacturing: excluded outside gate-to-gate scope
Pyrolysis (R-101)	LPG combustion for heating; process CO ₂ , CO, CH ₄ emissions from thermal oxidation	Reactor fabrication embodied energy: excluded from screening scope
Post-combustion gas treatment (F-101)	Thermal oxidation of pyrolysis vapors; flue gas CO ₂ emissions	Detailed gas-phase speciation: not available at this stage
Product collection and grinding (G-101)	Manual labor; marble mortar grinding	Machine-ground alternative: excluded manual process used
Product use phase	Excluded from gate-to-gate scope	Full use-phase LCA recommended in future work
End-of-life (spent SPB)	Excluded from gate-to-gate scope	Regeneration cycle data available but EOL allocation beyond scope

2.2.2. Life Cycle Inventory (LCI)

The life cycle inventory was constructed using primary process data derived from the co-pyrolysis system described in Section 2.1 and shown in Tables 4–6 and Figure 2, with supplementary cost and mass-balance information drawn from the accompanying economic analysis, and all inventory flows expressed per functional unit of 1 kg SPB-500 produced on the basis of a 35% *w/w* biochar yield at 500 °C. As tabulated in Tables 4–6, LCI per functional unit confirms gross gate-to-gate production emissions of +8.771 kg CO₂e kg^{−1} SPB-500. A separate consequential waste-diversion scenario was subsequently evaluated to estimate the potential effects of carbon sequestration and avoided-disposal emissions on the overall greenhouse-gas balance and allocation assumptions.

Table 4. Inputs and outputs (gate-to-gate inventory).

Input/Output Item	Quantity per kg SPB	Emission Factor	Unit	CO ₂ e per kg SPB
Inputs				
Sawdust feedstock	2.286	0 (waste-input rule)	kg	0
PP plastic waste feedstock	0.571	0 (waste-input rule)	kg	0
LPG fuel (R-101 burner)	1.143	2.983 kg CO ₂ e kg ^{−1} LPG	kg LPG	3.410
Electricity for drying (D-101)	4.286	0.5765 kg CO ₂ e kWh ^{−1}	kWh	2.471
Post-combustion of pyrolysis vapors, gases, and oils	0.788 kg C oxidized	44/12 kg CO ₂ kg ^{−1} C	kg C	2.890
Labor (manual handling)	2.857 person-h	Not quantified	–	–
Outputs				
SPB-500 product	1	–	kg	–
Gross gate-to-gate GHG emissions	–	–	–	+8.771

Table 5. Consequential waste-diversion scenario (not included in gate-to-gate inventory).

Credit Item	Quantity	Assumption	Unit	CO ₂ e Credit
Potential carbon-retention credit, conditional on safe EOL management	total carbon content in SPB-500, 0.844 kg C (CHNS analysis)	Stability factor, 0.80 (IBI criterion), Stable carbon content = 0.675 kg C	kg CO ₂ e	−2.477 (0.675 × 44/12)
Avoided landfill CH ₄ from sawdust diversion	2.286 kg sawdust	Alternative disposal scenario	kg CO ₂ e	−1.596
Avoided PP open burning	0.571 kg PP	Alternative disposal scenario	kg CO ₂ e	−1.616
Total consequential credits	–	–	–	−5.689

Table 6. Hybrid greenhouse-gas balance.

Indicator	Value
Gross gate-to-gate emissions	+8.771 kg CO ₂ e kg ^{−1} SPB
Total consequential credits	−5.689 kg CO ₂ e kg ^{−1} SPB
Net GHG balance (scenario-based), including conditional carbon-retention and waste-diversion credits	+3.082 kg CO ₂ e kg ^{−1} SPB

Note: Gross gate-to-gate emissions represent the attributional life cycle inventory within the defined system boundary. Carbon sequestration and avoided-disposal credits are reported separately as a consequential waste-diversion scenario and are not included in the gate-to-gate inventory. Therefore, the hybrid scenario-based net greenhouse-gas balance should be interpreted as a hybrid scenario-based indicator rather than a strict attributional LCA result.

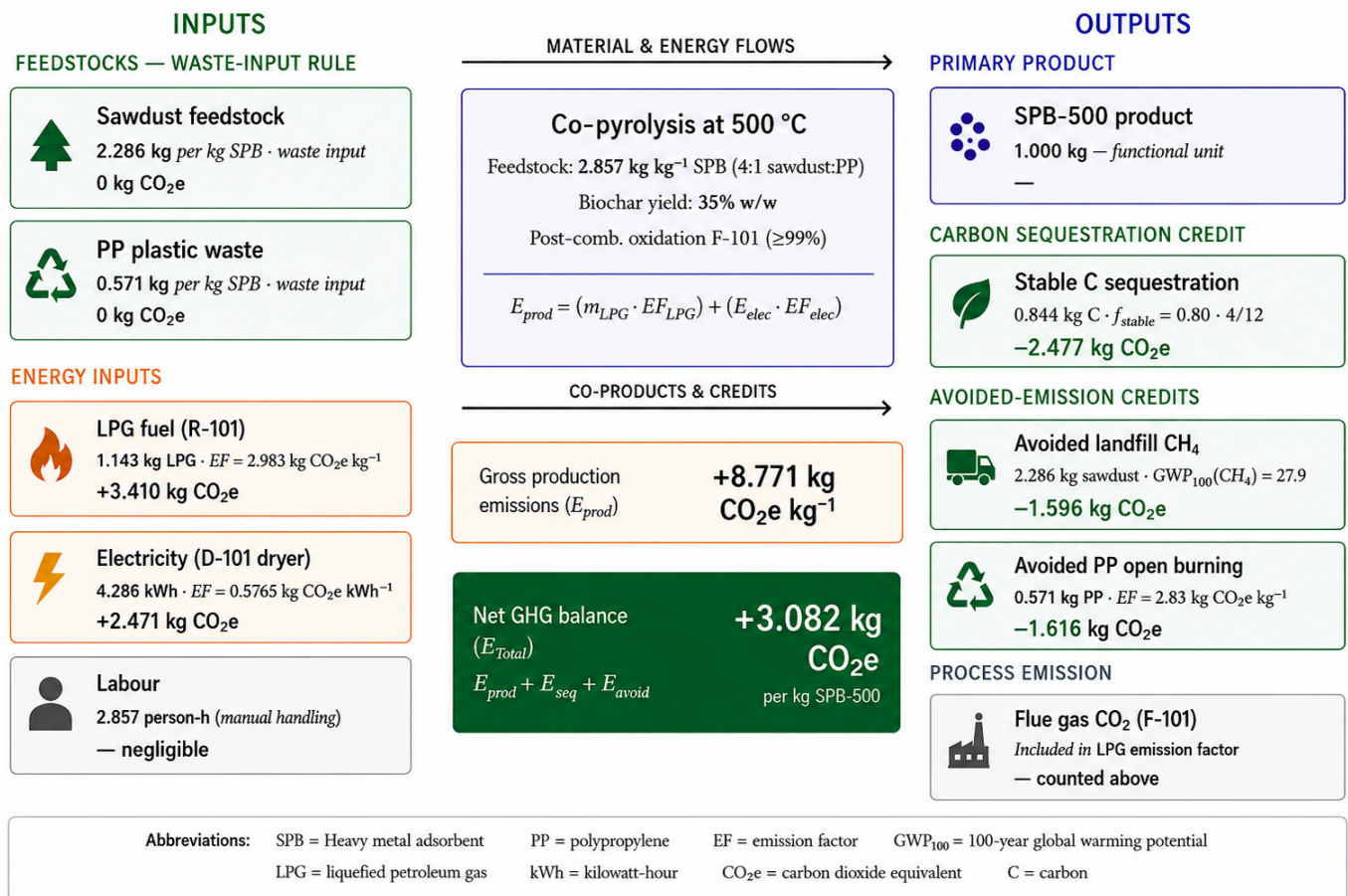


Figure 2. LCI flow diagram for the production of 1 kg sawdust–polypropylene biochar (SPB-500) by co-pyrolysis at 500 °C (functional unit = 1 kg SPB-500).

2.3. CO₂ Emission Assessment of SPB Co-Pyrolysis Production

A quantitative CO₂ emission assessment was conducted for the production of SPB at 500 °C to characterize both the gross greenhouse-gas (GHG) emissions attributable to the production process and the net carbon balance when stable carbon sequestration within the biochar product and avoided emissions arising from waste stream diversion are evaluated separately as a consequential waste-diversion scenario and are not included in the attributional gate-to-gate system boundary. All emission calculations are expressed per kilogram of SPB produced as the functional unit, maintaining consistency with the environmental screening framework established in Section 2.2. Emission factors were sourced exclusively from internationally recognized and peer-reviewed databases, specifically the IPCC 2006 Guidelines for National Greenhouse-Gas Inventories, the IPCC Sixth Assessment Report (AR6, 2021) [29], and the Thailand Greenhouse-Gas Management Organization (TGO, 2022) [30] national grid emission factor. Primary process data from Section 2.1 are applied throughout all calculations. The emission factors and their respective sources adopted in this assessment are summarized in Table 7.

Table 7. Emission factors applied in the CO₂ emission assessment.

Emission Source/Activity	Unit	Emission Factor	Value	Reference
LPG combustion (stationary)	kg CO ₂ e kg ^{−1} LPG	EF _{LPG}	2.983	IPCC 2006, Vol.2, Tier 1 [29]
Thai grid electricity	kg CO ₂ e kWh ^{−1}	EF _{elec}	0.5765	TGO Thailand 2022 [30]
Landfill CH ₄ from sawdust decomposition	kg CO ₂ e kg ^{−1} sawdust	EF _{saw}	0.698	IPCC 2006, Vol.5; GWP100 (CH ₄) = 27.9 AR6 [29]
Open burning of PP plastic waste	kg CO ₂ e kg ^{−1} PP	EF _{PP}	2.83	IPCC 2006, Vol.5, Annex 3 [29]
Carbon sequestration in stable biochar	kg CO ₂ e kg ^{−1} C in biochar	EF _{Cseq}	−3.667	Stoichiometric: 44/12 CO ₂ :C ratio
Biochar carbon stability factor (f _{stable})	Dimensionless	f _{stable}	0.80	IBI criterion (H/C _{org} < 0.4)

Note: GWP₁₀₀ of CH₄ = 27.9 kg CO₂e. LPG emission factor includes CO₂ (2.921 kg kg^{−1}) + CH₄ (0.062 kg CO₂e kg^{−1}). Landfill CH₄ factor: 0.025 kg CH₄ kg^{−1} organic waste × GWP 27.9 = 0.698 kg CO₂e kg^{−1}. Carbon stability factor of 0.80 reflects the fraction of biochar carbon that persists in soil over >100 years under temperate conditions; H/C_{org} (0.022) calculated confirmed <0.4 for SPB-500 sample.

The total CO₂ emission per kg SPB produced (E_{total}) is calculated as the algebraic sum of direct production emissions (E_{prod}), stable carbon sequestration credits (E_{seq}), and avoided waste disposal emission credits (E_{avoid}):

$$E_{\text{total}} = E_{\text{prod}} + E_{\text{seq}} + E_{\text{avoid}} \quad (1)$$

$$E_{\text{prod}} = (m_{\text{LPG}} \times \text{EF}_{\text{LPG}}) + (E_{\text{elec}} \times \text{EF}_{\text{elec}}) + E_{\text{post}} \quad (2)$$

$$E_{\text{seq}} = -(C\%_{\text{SPB}} \times m_{\text{SPB}} \times f_{\text{stable}} \times \text{EF}_{\text{Cseq}}) \quad (3)$$

$$E_{\text{avoid}} = -(m_{\text{saw}} \times \text{EF}_{\text{saw}}) - (m_{\text{PP}} \times \text{EF}_{\text{PP}}) \quad (4)$$

where m_{LPG} refers to the amount of LPG used per kg of SPB (kg LPG per kg SPB); E_{elec} refers to the electricity used per kg of SPB (kWh per kg SPB); $C\%_{\text{SPB}}$ refers to the carbon content of the SPB product in a mass fraction determined by CHNS analysis (84.43%); $m_{\text{SPB}} = 1$ kg per functional unit; f_{stable} refers to the IBI carbon stability factor, which is 0.80; EF_{Cseq} refers to −3.667 kg CO₂e per kg C; m_{saw} refers to the amount of sawdust used per kg of SPB (kg per kg SPB); m_{PP} refers to the amount of PP used per kg of SPB (kg per kg SPB); E_{post} represents the greenhouse-gas emissions associated with the post-combustion of pyrolysis vapors, gases, and bio-oil generated during the co-pyrolysis process.

The carbon balancing results depend on the following assumptions regarding the stability of carbon stored in biochar, the reduction in the emissions from landfills by diverting the sawdust waste stream, and the prevention of any emissions that might arise due to the open burning of polypropylene waste. Therefore, the credits earned are more appropriately viewed as scenario projections and not actual results. The gross production emissions (E_{prod}) represent attributional gate-to-gate emissions associated with SPB-500 production. In contrast, E_{seq} and E_{avoid} represent consequential credits associated with long-term carbon retention and hypothetical waste-diversion scenarios. Therefore, the reported hybrid scenario-based net greenhouse-gas balance should be interpreted as a hybrid screening indicator rather than a strictly attributional gate-to-gate LCA result. Furthermore, the carbon-retention credit reported in this study assumes environmentally sound end-of-life (EOL) management capable of preserving long-term carbon storage. No specific EOL pathway, such as regeneration, heavy-metal stabilization, landfill disposal, incineration, or beneficial reuse of spent Cu-loaded SPB-500, was explicitly modeled in

this screening assessment. Consequently, the reported carbon-retention credit should be interpreted as a scenario-based estimate rather than a demonstrated environmental outcome. Future cradle-to-grave life cycle assessments should evaluate alternative EOL management strategies and their influence on carbon retention, heavy-metal stabilization, and overall environmental performance.

2.4. Social Return on Investment (SROI) Analysis

An SROI analysis was carried out according to the SROI Network principles to quantify the social, environmental, and economic co-benefits that are generated by the SPB project apart from its direct economic effects. The analysis adopts a forward-looking evaluative perspective applied to a community-scale deployment scenario in rural Chaiphaphum Province, with all values reported in THB and USD (35.8 THB USD⁻¹; Bank of Thailand, 2024) [31] and discounted at 5% per annum over a five-year horizon. The SROI boundary encompasses one decentralized SPB production and water treatment facility (1200 kg SPB year⁻¹; 10 m³ month⁻¹) serving 50 rural households. Key assumptions include the following: (i) SPB-500 achieves up to approximately 90% heavy-metal removal under the experimental operating conditions (adsorbent dosage of 1 g per 100 mL and inlet Cu²⁺ concentrations up to 200 mg L⁻¹); (ii) five regeneration cycles maintaining ≥73% removal efficiency; (iii) without the project, contaminated wastewater would be discharged to adjacent waterways; (iv) sawdust and PP waste would otherwise be openly burned and landfill-disposed, respectively; and (v) two full-time equivalent positions are generated over the operational period. Since the outcomes of SROI are based on various assumptions regarding attribution, deadweight, displacement, drop-off, and the monetization of proxy measures for the social value, sensitivity analyses have been undertaken to examine the validity of the computed SROI ratio under different assumptions. Therefore, the SROI numbers are not directly observed but are to be considered approximations of the SROI ratios. However, financial proxies and assumptions used in assessing deadweight, attribution, displacement, and drop-off effects were mainly sourced from academic literature, readily available economic information, and scenario-based analysis. The analysis did not consider any data gathered through social impact assessment or stakeholders' opinions or even information from the local authorities. For this reason, the calculated SROI figures are expected to be scenario-based figures, but not actual social impacts.

For benchmarking, the main benchmark chosen for this study involves the use of commercial-activated carbon (GAC/PAC) as SPB-500 was designed specifically to be an affordable adsorbent meant to replace commercial adsorption products for the purpose of removing heavy metals. Thus, all economic and environmental comparisons will be made against commercially viable products. Furthermore, comparisons were made through the literature based on biomass pyrolysis and biomass-plastic pyrolysis biochar.

3. Results and Discussion

3.1. Capital Expenditure and Operating Expenditure and Production Cost per Kilogram

Capital expenditure (CAPEX) for the fabricated local SPB co-pyrolysis plant was 46,000 THB (1286 USD) in which the SS-based pyrolysis reactor was the highest component (54.3%) of the expense, followed by the drying unit, the LPG burner, and other components (Figure 3a,b). Capital costs were reduced by 15–400 folds when compared to existing industrial pyrolysis processes due to the application of locally available components coupled with LPG technology. When all other civil expenses have been considered, the estimate of CAPEX is not high even when taking into account the regulations (i.e., 60,000 THB, 1676 USD). Operating expenditure (OPEX) per batch was 110.55 THB (3.09 USD) for producing a biochar batch at 35%, resulting in a cost per kilogram of 316 THB/kg (8.8 USD/kg).

Labor was the biggest OPEX (72.4%) followed by maintenance, LPG consumption, and electrical power consumption, whereas no expenses were considered for the cost of the raw materials due to their nature being waste materials (Figure 3c). With mechanization and automation for grinding process, cost could be reduced up to 130–160 THB/kg (3.6–4.5 USD/kg), with the utilization of syngas recycling as further potential for LPG substitution and OPEX saving. The sensitivity analysis considering the variation in yield of 5% produced a unit cost of production between 276 and 369 THB/kg (7.7–10.3 USD/kg).

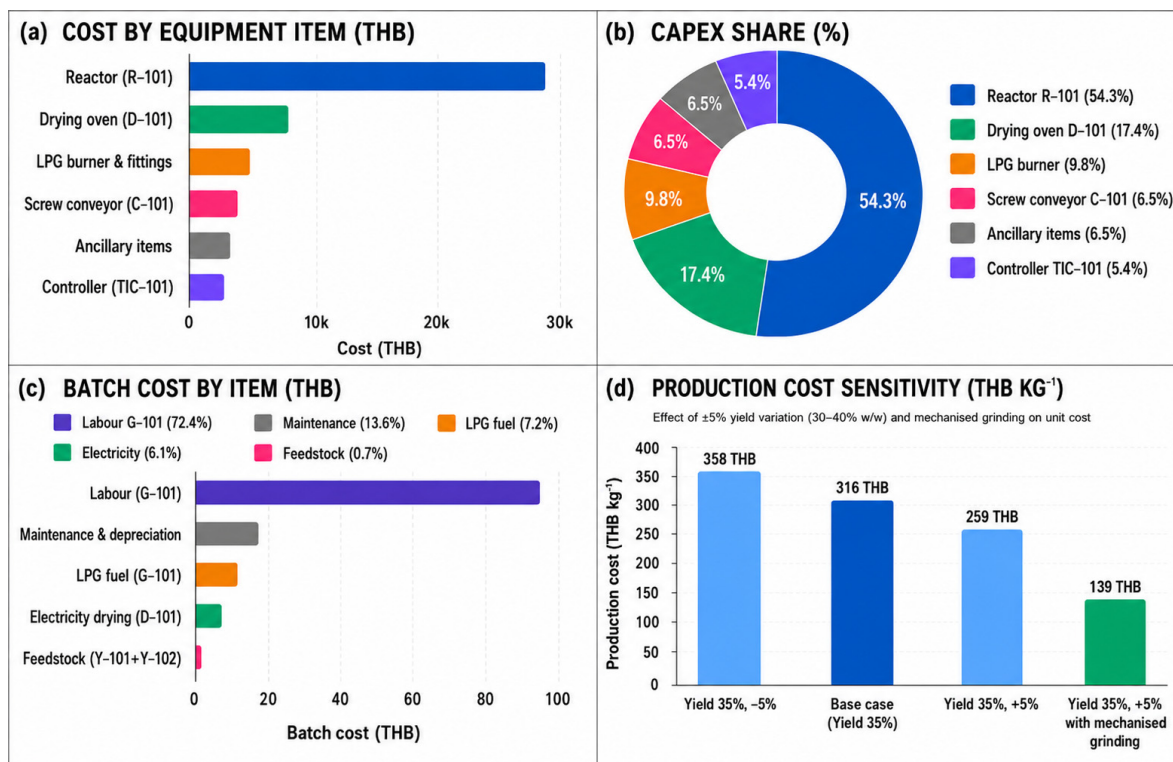


Figure 3. Techno-economic analysis of the locally fabricated sawdust–polypropylene (SPB-500) co-pyrolysis production system.

3.2. Simple Payback Calculation, Circular Economy, and Waste-Valorization Benefits

The economic feasibility of the proposed community-scale SPB-500 production plant was assessed based on the annual production capacity of 1200 kg (roughly 100 kg month⁻¹). The main economic variables used in this study include CAPEX, OPEX, unit production cost, production capacity, selling price, and cost saving resulting from the reduced requirement for activated carbon. All these variables are briefly shown in Figure 4a. With respect to the calculated annual production cost of SPB-500 according to the results from the previous batch-scale experiment (316 THB kg⁻¹ in Table 2), the annual amount of OPEX was estimated to be 379,200 THB year⁻¹. According to a conservative estimation of the selling price of 40 USD kg⁻¹ or about 1432 THB kg⁻¹ for SPB-500 production, the projected annual income is expected to be 1,718,400 THB year⁻¹. Thus, the annual net profit is estimated to be around 1,339,200 THB year⁻¹. An extensive assessment of the annual economic parameters and payback period calculation is presented in Figure 4b. Considering the rather inexpensive CAPEX of about 46,000 THB for the locally developed pyrolysis reactor, the simple payback period can be assumed to be less than one year. This satisfactory performance is primarily due to the usage of cheap raw materials, less need for investment in the reactor, and the absence of chemical activation process in the commercial production of activated carbons. In addition, the cost of SPB-500 is notably cheaper compared to the prices of GAC and PAC available in the market. The relatively cost-effective production of

SPB-500, GAC, and PAC are illustrated in Figure 4d. In order to conduct long-term financial feasibility of the proposed system, a cumulative cash flow analysis was performed for the first 12 months of operation. As seen from Figure 4c, the revenue grows gradually in time, whereas operating costs are rather low, leading to rapid positive cash flow and payback of the initial investment even within the first month. In other words, the obtained results show promise in terms of potential economic advantages of SPB-500 production in communities. Under the in-house use case, SPB-500 could replace commercial-grade granular-activated carbon (GAC) to some extent in applications for heavy-metal adsorption. Based on the annual adsorbent consumption rate of $1200 \text{ kg year}^{-1}$ and considering a typical price of GAC at 80 USD kg^{-1} , the total savings due to avoiding purchase of the adsorbent could amount to $96,000 \text{ USD year}^{-1}$ gross. Nevertheless, with the expected production cost of SPB-500 of 8.8 USD kg^{-1} , the annual production costs would be $10,560 \text{ USD year}^{-1}$, thus leading to net savings of about $85,440 \text{ USD year}^{-1}$.

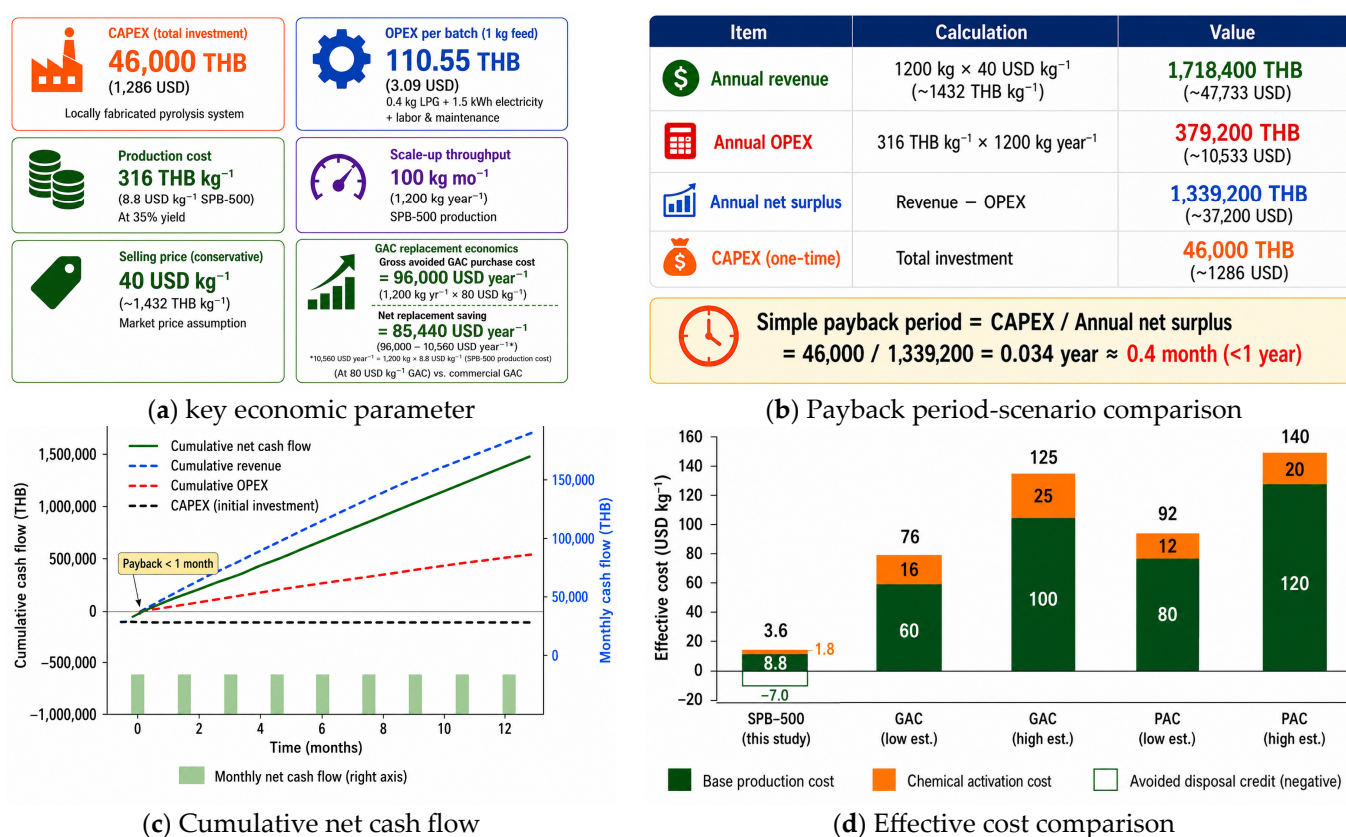


Figure 4. Techno-economic evaluation of community-scale SPB-500 production: (a) key economic parameters; (b) annual economic summary and payback calculation; (c) cumulative cash flow profile during the first 12 months of operation; and (d) effective production cost comparison between SPB-500 and commercial adsorbents.

It is important to stress here that this comparison is made based on cost per unit of mass production and not on adsorption efficiency per se. This implies that, since there might be variations in performance between SPB-500 and commercial-grade GAC, a one-to-one substitution cannot be performed without evaluating adsorption capacity, breakthrough curve performance during continuous flow, efficiency of regeneration, adsorbent lifetime, interaction with the matrix of real water, and costs per-unit mass of contaminants removed. However, it should be noted that this study only constitutes a preliminary economic assessment of the technology. Additional research should be done regarding scaling-up experiments with performance assessments and optimizations. In Figure 4d, therefore, the

comparison should be interpreted as a preliminary economic and environmental benchmark rather than evidence of direct functional substitutability between SPB-500 and commercial-activated carbons.

It should be emphasized that the projected annual production capacity (1200 kg SPB-500 year⁻¹), economic performance, and associated SROI results represent scenario-based screening estimates derived from a simplified community-scale deployment scenario. These results are intended to evaluate the potential feasibility of future implementation and should not be interpreted as experimentally demonstrated community-scale reactor performance.

3.3. Gross Gate-To-Gate Emissions

As shown in Table 8, SPB-500 demonstrated promising environmental performance relative to the literature-reported values for commercial-activated carbon. These comparisons should be interpreted as preliminary environmental benchmarks because differences in feedstock, production processes, adsorption performance, and system boundaries may influence the reported results. Gross attributional gate-to-gate greenhouse-gas emissions were estimated at +8.771 kg CO₂e kg⁻¹ SPB-500. These emissions originated from three sources: LPG combustion (+3.410 kg CO₂e kg⁻¹; 38.9%), electricity consumption during feedstock drying (+2.471 kg CO₂e kg⁻¹; 28.2%), and post-combustion of pyrolysis vapors, gases, and bio-oil (+2.890 kg CO₂e kg⁻¹; 32.9%). A separate consequential waste-diversion scenario was subsequently evaluated. When carbon sequestration and waste-diversion credits were considered, the resulting hybrid scenario-based net greenhouse-gas balance decreased to +3.082 kg CO₂e kg⁻¹ SPB-500. The comparatively low GWP100 was attributed to the lower thermal energy demand of LPG-fired pyrolysis at 500 °C relative to conventional high-temperature-activated carbon production. On a performance-normalized basis, the GWP100 of 0.047 g CO₂e g⁻¹ Cu²⁺ removed was within the lower range reported for commercial GAC. Net cumulative energy demand (CED) was approximately 57.6 MJ kg⁻¹, substantially lower than reported GAC values due to the absence of chemical activation and the utilization of waste-derived feedstocks. Based on literature benchmarking, the SPB-500 production pathway is expected to exhibit lower eutrophication and human-toxicity burdens than commercial-activated carbon production; however, quantitative midpoint characterization was beyond the scope of the present study. Furthermore, the high carbon sequestration credit reflected the elevated stable carbon content of SPB-500 (84.43% C; H/C_{org} = 0.022), indicating the formation of a highly stable aromatic carbon matrix during co-pyrolysis at 500 °C.

Table 9 provides a broader environmental benchmarking of SPB-500 against four commercially available adsorbent types, covering GWP100, production energy demand, chemical activation requirements, and qualitative scores for eutrophication and toxicity potential. The comparison demonstrates that SPB-500 achieves a scenario-based greenhouse-gas assessment net GWP100 of +3.082 kg CO₂e kg⁻¹ when avoided waste emission credits are included, making it one of the most environmentally favorable adsorbent options. This compares favorably to GAC (3.5–9.0 kg CO₂e kg⁻¹), PAC (4.0–10.0 kg CO₂e kg⁻¹), and ion-exchange resin (12–25 kg CO₂e kg⁻¹). The absence of chemical activation reagents represents a particularly important advantage, as KOH and ZnCl₂ activation of GAC generates substantial wastewater treatment burdens and contributes to freshwater eutrophication and ecotoxicity impacts that are entirely absent from the SPB process.

Table 8. Environmental screening results per kg SPB-500 produced, with comparison to GAC production.

Impact Category	Unit	SPB-500 (This Study)	Commercial GAC (Literature)	Comparison with GAC
Gross GWP100 (production only)	kg CO ₂ e kg ⁻¹	+8.771	3.5–9.0 [28,32]	Within reported literature range
Net GWP100 (hybrid scenario-based)	kg CO ₂ e kg ⁻¹	+3.082	3.5–9.0 (no consequential credits) [29]	Approximately 0.4–5.9 kg CO ₂ e kg ⁻¹ lower
GWP100 per g Cu ²⁺ removed (functional unit basis)	g CO ₂ e g ⁻¹ Cu ²⁺ removed	0.047	0.044–0.113 [33]	Within lower reported range
Cumulative Energy Demand (CED)	MJ kg ⁻¹	57.6	50–120 [28,32]	Lower to comparable
Freshwater Eutrophication Potential (FEP)	Qualitative	Low (no chemical activation reagents)	Moderate (KOH/ZnCl ₂ activation) [34]	Lower (qualitative benchmark)
Human-Toxicity Potential (HTP)	Qualitative	Low (LPG combustion with post-combustion control)	Moderate (chemical activation and coal-derived emissions) [35]	Lower (qualitative benchmark)
Land use	Qualitative	Negligible (waste-derived feedstocks)	Low–moderate (biomass cultivation/mining) [29,36]	Lower
Potential carbon-retention credit *	kg CO ₂ e kg ⁻¹	−2.477	Variable (−0.5 to −2.0) [37]	Higher potential credit

Note: * Potential carbon-retention credit is a scenario-based estimate assuming long-term stable carbon storage under appropriate end-of-life management. It does not represent a verified carbon credit or actual CO₂ removal.

Table 9. Comparative environmental benchmarking of SPB-500 versus commercial adsorbents for heavy-metal removal.

Adsorbent	GWP (kg CO ₂ e kg ⁻¹)	Net GWP (with Credits)	CED (MJ kg ⁻¹)	Activation Chemicals	FEP	HTP
SPB-500 (this study)	+8.771	+3.082 ★	~57.6	None	Low	Low
Commercial biochar (typ.) [28]	2.0–5.0	−0.5 to +2.0	20–60	Sometimes	Low–mod.	Low–mod.
GAC (granular-activated carbon) [32,38]	3.5–9.0	3.5–9.0 (no credit)	50–120	Yes (KOH/ZnCl ₂)	Moderate	Moderate
PAC (powdered-activated carbon) [39]	4.0–10.0	4.0–10.0	60–130	Yes (H ₃ PO ₄)	Moderate	Moderate
Synthetic zeolite [40]	5.0–12.0	5.0–12.0	80–180	N/A	Low	Low
Ion-exchange resin [41]	12–25	12–25	200–400	N/A (synthetic)	Moderate	High

Note: ★ = scenario-based greenhouse-gas assessment under waste valorisation conditions. FEP and HTP are qualitative literature-based benchmarking indicators and do not represent quantified midpoint LCIA results.

3.4. CO₂ Emission Analysis for SPB-500 Production

The process input parameters underpinning the CO₂ emission calculations are compiled in Table 10, with all values expressed per kilogram of SPB-500 produced as the functional unit.

Table 10. Process input parameters per kg SPB produced at each pyrolysis temperature.

Parameter	SPB-500	Source/Assumption
Biochar yield (% <i>w/w</i> of feedstock)	35%	Lit. slow pyrolysis, lignocellulosic-PP blends
Feedstock input per kg SPB (kg)	2.857	=1/yield fraction
Sawdust input per kg SPB (kg) [4:1 ratio]	2.286	=feedstock $\times$ 0.80
PP plastic input per kg SPB (kg) [4:1 ratio]	0.571	=feedstock $\times$ 0.20
LPG consumed per kg SPB (kg LPG)	1.143	=0.4 kg batch ^{−1} /yield fraction
Electricity for drying per kg SPB (kWh)	4.286	=1.5 kWh batch ^{−1} /yield fraction
Carbon content of SPB (wt.%, CHNS Table 2)	84.43%	Measured, CHNS analysis (LECO CHN628)
Stable C in biochar (kg per kg SPB)	0.675	=C% $\times$ 1 kg $\times$ f_{stable} (0.80)

The step-by-step CO₂ emission calculation for SPB-500, presented in Table 11, is structured as the algebraic sum of gross production emissions and three credit streams.

Table 11. Step-by-step CO₂ emission calculation for SPB-500 (pyrolysis at 500 °C).

Step	Emission Source or Credit	Calculation	Value	Unit	kg CO ₂ e kg ^{−1} SPB
GROSS EMISSIONS					
1	LPG combustion (R-101 burner)	1.143×2.983	1.143	kg LPG	+3.410
2	Grid electricity drying (D-101)	4.286×0.5765	4.286	kWh	+2.471
3	Post-combustion of vapors/gases/oils	0.788×3.667	0.778	kg C	+2.890
	Gross production emission (E_{prod})	Step 1 + Step 2 + Step 3			+8.771
CREDITS					
3	Stable C sequestration in biochar	$0.675 \times (-3.667)$	0.675	kg C	−2.477
4	Avoided landfill CH ₄ sawdust	2.286×0.698	2.286	kg Sawdust	−1.596
5	Avoided open-burning PP plastic	0.571×2.830	0.571	kg PP	−1.616
	Total credits	Step 3 + Step 4 + Step 5			−5.687
	NET CO ₂ e balance (E_{total})	E_{prod} + credits			+3.082 (scenario-based greenhouse-gas assessment) ★

Note: ★ = scenario-based greenhouse-gas assessment under waste valorisation conditions. FEP and HTP are qualitative literature-based benchmarking indicators and do not represent quantified midpoint LCIA results.

Gross production-phase emissions arise exclusively from LPG combustion in unit R-101 (Step 1: $1.143 \times 2.983 = +3.410$ kg CO₂e kg^{−1}) and grid electricity consumption for oven drying in unit D-101 (Step 2: $4.286 \times 0.5765 = +2.471$ kg CO₂e kg^{−1}), totaling $E_{\text{prod}} = +8.771$ kg CO₂e kg^{−1} SPB-500. The corresponding percentage contributions were 38.9% for LPG combustion, 28.2% for electricity use, and 32.9% for post-combustion emissions. Against this gross burden, three credit streams are applied: stable carbon sequestration in the biochar product (Step 3: $0.675 \times 3.667 = -2.477$ kg CO₂e kg^{−1}), avoided landfill methane emissions from sawdust diversion (Step 4: $2.286 \times 0.698 = -1.596$ kg CO₂e kg^{−1}; GWP100 (CH₄) = 27.9, IPCC AR6), and avoided open-burning emissions from PP plastic diversion (Step 5: $0.571 \times 2.830 = -1.616$ kg CO₂e kg^{−1}; IPCC 2006 [28], Vol. 5, Annex 3). The three credit streams collectively yield a total credit of -5.687 kg CO₂e kg^{−1}, which does not exceed the gross production burden of $+8.771$ kg CO₂e kg^{−1}, resulting in a hybrid scenario-

based net greenhouse-gas balance of $E_{\text{total}} = E_{\text{prod}} + E_{\text{seq}} + E_{\text{avoid}} = +3.082 \text{ kg CO}_2\text{e kg}^{-1}$ SPB-500, confirming that the production pathway is unambiguously net scenario-based greenhouse-gas assessment under the adopted gate-to-gate system boundary.

As illustrated in Figure 5a, the hybrid scenario-based net greenhouse-gas balance of SPB-500 ($+3.082 \text{ kg CO}_2\text{e kg}^{-1}$) is less sharp than the scenario-based greenhouse-gas assessment profiles of commercial GAC ($+3.5$ to $+9.0 \text{ kg CO}_2\text{e kg}^{-1}$), PAC ($+4.0$ to $+10.0 \text{ kg CO}_2\text{e kg}^{-1}$), and commercial biochar (-0.5 to $+3.0 \text{ kg CO}_2\text{e kg}^{-1}$), supporting its potential application under the evaluated scenario of approximately 0.4 – $5.9 \text{ kg CO}_2\text{e kg}^{-1}$ lower than reported values for commercial-activated carbon (3.5 – $9.0 \text{ kg CO}_2\text{e kg}^{-1}$). Notably, the gross production-phase GWP100 of SPB-500 ($+8.771 \text{ kg CO}_2\text{e kg}^{-1}$; Figure 5b) already falls within or below the lower bound of the GAC literature range prior to credit application, reflecting the intrinsic thermal efficiency advantage of LPG-fired slow pyrolysis at 500°C relative to industrial rotary kiln activation at 700 – 900°C . The scenario-based greenhouse-gas assessment classification arises from three reinforcing mechanisms, each visible in the waterfall decomposition of Figure 5a. First, waste-input classification of both feedstocks under ISO 14044 Annex B eliminates all upstream production burdens and generates two avoided-emission credit landfill CH_4 avoidance ($-1.596 \text{ kg CO}_2\text{e kg}^{-1}$) and PP open-burning avoidance ($-1.616 \text{ kg CO}_2\text{e kg}^{-1}$), which is a structural advantage unavailable to fossil-derived or virgin-biomass adsorbents. Second, the thermally stable aromatic carbon matrix formed during co-pyrolysis at 500°C permanently sequesters $0.675 \text{ kg C kg}^{-1}$ SPB over timescales exceeding 100 years ($\text{H}/\text{C}_{\text{org}} = 0.022$; this is well below the IBI stability threshold of 0.4), contributing the largest individual credit of $-2.477 \text{ kg CO}_2\text{e kg}^{-1}$. It needs to be recognized that the estimated GHG balance depends on assumptions related to the stability of carbon in biochar, reduced methane from landfills, and reduced emissions from open burning. Any changes in these values would have an impact on the scale of credits that could be gained, but it can be said with certainty that SPB-500 will always have significantly less carbon footprint compared to standard AC production. Third, the comparatively low pyrolysis temperature constrains gross energy consumption such that the SPB-500 gross GWP100 remains below the mid-range of GAC even before credit streams are applied (Figure 5b). Despite having selected LPG for being available, easy to operate, and commonly used in rural areas in Thailand, a comparative evaluation of other fuel sources for cooking, including biomass pellets and natural gas, was beyond the scope of this project.

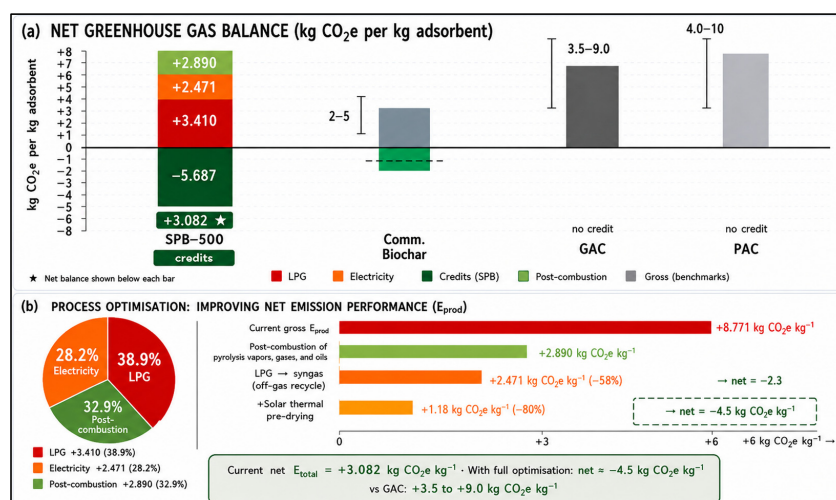


Figure 5. Net scenario-based greenhouse-gas assessment production of SPB-500 versus scenario-based greenhouse-gas assessment conventional adsorbents: step-by-step emission accounting and environmental hotspot analysis.

3.5. Total Investment (Inputs), Outcomes, Indicators and Financial Proxies

The total amount of money required to implement the community-scale SPB-500 over the period of five years was estimated to be 4,342,000 THB. It includes capital investment, operating costs, manpower costs, R&M effort, and absorption-system infrastructure investment (Table 12).

Table 12. Total investment (inputs) over the 5-year SROI analysis period.

Input Item	Year 1 (THB)	Years 2–5 p.a. (THB)	5-Year Total (THB)	Contributor	Input Item
CAPEX reactor + equipment	46,000	0	46,000	University/grant	CAPEX reactor + equipment
Annual OPEX (production cost basis)	379,200	379,200	1,896,000	Project budget	Annual OPEX (production cost basis)
Labor (2 FTE operators)	384,000	384,000	1,920,000	Local employment	Labor (2 FTE operators)
Research/monitoring costs	120,000	60,000	360,000	University	Research/monitoring costs
Adsorption system (columns, plumbing)	80,000	10,000	120,000	Municipality/project	Adsorption system (columns, plumbing)
Total investment	1,009,200	833,200	4,342,000	—	Total investment

Manpower costs (1,920,000 THB; 44.2%) and operating costs (1,896,000 THB; 43.7%) comprised the largest shares of capital outlay, thus highlighting the importance of the workforce involved and manufacturing efforts to achieve SPB-500 community-scale implementation. SROI outcome framework is illustrated in Figure 6, while the indicators, financial proxies, and adjustment factors are summarized in Table 13. There were nine monetized outcomes (O1–O9) evaluated within four stakeholder-benefit categories: (i) public health and water quality improvement, (ii) environmental remediation and waste valorization, (iii) socioeconomic development, and (iv) institutional value creation. After deadweight, attribution, and drop-off adjustments, the highest Year-1 value was observed for water quality improvement (O1; 641,250 THB year^{−1}), followed by the reduction in health risks (O2; 288,000 THB year^{−1}) and diversion of sawdust (O3; 213,300 THB year^{−1}).

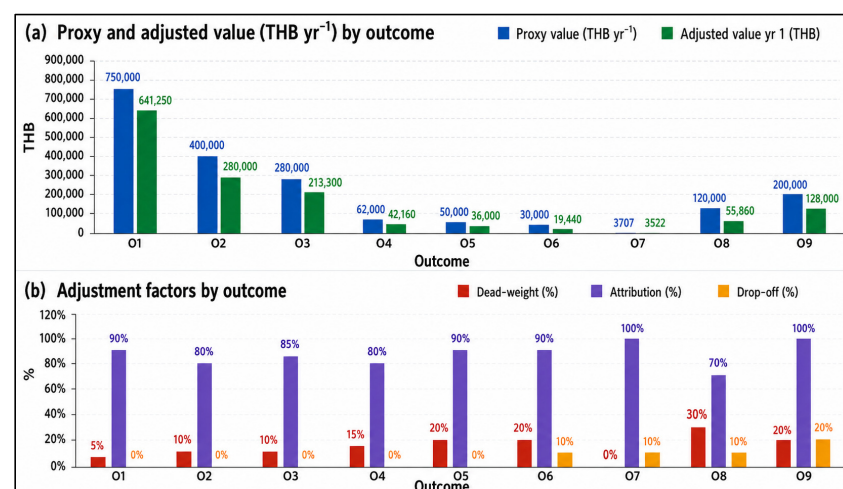


Figure 6. SROI outcome map for community-scale SPB-500 co-pyrolysis deployment: comparison of unadjusted proxy values and adjusted Year 1 social values (THB) across nine outcome streams (O1–O9), with corresponding SROI adjustment factors (deadweight, attribution, and drop-off).

Table 13. Outcome map with indicators, financial proxies, and SROI adjustment factors.

Outcome	Indicator	Financial Proxy	Proxy Value (THB yr ⁻¹)	Dead-weight	Attribution	Drop-Off	Adjusted Value yr 1 (THB)
O1: Improved water quality for 50 households	Improved Cu ²⁺ removal and wastewater quality under the experimental conditions	Avoided bottled-water expenditure (alternative water supply cost only)	750,000	5%	90%	0%	641,250
O2: Reduced health risk Cu ²⁺ exposure	Number of households with access to Cu ²⁺ that improved Cu ²⁺ removal and wastewater quality under the experimental conditions	Avoided healthcare costs associated with Cu-related illness (cost-of-illness approach)	400,000	10%	80%	0%	288,000
O3: Diversion of sawdust from open burning	Tonnes of sawdust diverted per year (2.857 kg/kg SPB × 1200 kg/yr = 3.43 t/yr)	Avoided air pollution cost: PM2.5 health impact + CO ₂ e carbon price (35 USD t ⁻¹)	280,000	10%	85%	0%	213,300
O4: Diversion of PP plastic from landfill/illegal dump	Tonnes of PP diverted (0.571 kg/kg SPB × 1200 = 0.685 t/yr)	Avoided landfill cost + avoided marine pollution cost (250 USD t ⁻¹ social cost)	62,000	15%	80%	0%	42,160
O5: Local employment creation	2 FTE jobs created for local operators/technicians	Well-being value of employment (Fujiwara et al. proxy: 25,000 THB/FTE/yr above wage)	50,000	20%	90%	0%	36,000
O6: Skills and capacity building	Number of operators trained in pyrolysis and water treatment	Value of equivalent vocational training course (market rate)	30,000	20%	90%	10%	19,440
O7: Carbon sequestration (stable C in biochar)	kg CO ₂ e sequestered per year: 0.675 kg C/kg SPB × 1200 × 3.667 = 2970 kg CO ₂ e yr ⁻¹	Carbon credit price: 35 USD t ⁻¹ CO ₂ e (Thai voluntary carbon market estimate)	3707	0%	100%	10%	3522
O8: Reduced industry compliance risk (sawmill + PP supplier)	Reduced regulatory fines/penalties for illegal waste disposal	Average environmental fine avoided (PCD Thailand, solid waste violation)	120,000	30%	70%	10%	55,860
O9: Knowledge and research value	Peer-reviewed publication in high-impact journal; accessible data	Estimated grant equivalent and knowledge externality (bibliometric proxy)	200,000	20%	100%	20%	128,000
Total							1,427,532

Figure 6 shows that outcomes O1 and O2 contributed to about 65.13% of the adjusted Year-1 social value. Thus, water quality improvement and the improvement in public health can be viewed as the primary social value-generating activities. Other monetized outcomes included waste management, carbon sequestration, job creation, skill development, reduced compliance risk, and knowledge generation. The financial proxies were estimated based on the expenses avoided because of bottled water, health-related expenses avoided due to improved health, expense avoidance in waste management and the prevention of pollution, carbon credits, vocational training costs, compliance fines, and research cost equivalents. Deadweight rates were set at 0% for carbon sequestration and 30% for compliance-risk reduction in order to provide a conservative estimation of the social value. All the outcomes considered in Table 11 and Figure 6 provide the basis for the present value and SROI calculations discussed in Sections 3.6 and 3.7.

3.6. Present Value of Outcomes

Each outcome value was discounted per annum over the five-year analysis period and adjusted using the deadweight, attribution, and drop-off factors specified in Table 13. The present value (PV) of each outcome is calculated as

$$PV(O_i) = \text{Adjusted Year 1 Values} \times \frac{\left[\sum_{t=1}^5 (1 - d)^t \right]}{(1 + 0.05)^t} \quad (5)$$

where d denotes the outcome-specific annual drop-off rate and t is the year index from one to five.

The outcomes O1–O9 can be summarized using Table 14 and Figure 7. In particular, the outcomes O1–O5 were expected to maintain the adjusted benefits throughout the entire five years' period, hence being affected only by the annual discounting effect. Accordingly, benefits such as water quality improvements, health risk reductions, waste management benefits, and employment creation remained constant throughout the assessment period. In turn, the outcomes O6–O9 were expected to suffer from annual drop-off rates of 10%, 5%, 5%, and 20%, respectively. The total present value (PV) of the nine outcomes streams during the five-year assessment period at a discount rate of 5% was expected to equal 6,025,841 THB. With a revised total investment of 4,342,000 THB (Table 10), the base-case SROI would be 1.39:1, implying that for each 1 THB invested into a project, there would be generated a net gain of about 1.39 THB in terms of social, environmental, and economic value. Water quality improvement (O1) became the leading outcome of the project, with about 46.1% share of PV in the total one. It was followed by health risk reduction (O2; 20.7%) and sawdust diversion (O3; 15.3%). Overall, O1 and O2 were responsible for creating around 66.9% of social value generated by the project, which indicated that public health and water quality benefits played a significant role in the overall benefits of the proposed deployment framework. Environmental waste-diversion benefits (O3 and O4) were responsible for 18.4% of PV, whereas employment creation and skills development (O5 and O6) for 3.7%. Knowledge generation benefits (O9) became less relevant with the passage of time because of their annual drop-off rate of 20%. Together, carbon sequestration (O7) and compliance-risk reduction (O8) made up 3.5% of PV. In this regard, it should be acknowledged that the relatively small contribution of O7 is caused by the current undervaluation of carbon credits in the Thai voluntary carbon market and not because of some limitations in SPB-500's ability to store carbon.

3.7. SROI Ratio, Sensitivity Analysis and SDGs

As seen in Table 15 and Figure 8a, the new base-case SROI ratio of 1.39:1 means that, in terms of social, environmental, and economic benefits, the community-scale implementation of SPB-500 will result in a benefit ratio of 1.39 THB for each 1 THB spent on the project. While it is smaller compared to the former estimate based on the old investment base, this number still exceeds one, which shows that the SROI is positive. Moreover, as is demonstrated by the sensitivity analysis results, the project's investment case proves rather resilient with SROI ratios ranging between 1.13:1 and 1.51:1. These SROI figures depend on the proxies used and the assumptions about attribution, deadweight, displacement, and drop-off. They should thus be regarded as estimates, based on scenarios, rather than being seen as actual social impacts.

Table 14. Present value (PV) calculation of adjusted outcomes over the 5-year assessment period.

Outcome	Adj. Year 1 Value (THB)	PV Year 1	PV Year 2	PV Year 3	PV Year 4	PV Year 5	Total PV (THB)
O1—Water quality improvement	641,250	610,714	581,632	553,935	527,557	502,436	2,776,274
O2—Health risk reduction	288,000	274,286	261,224	248,785	236,938	225,655	1,246,888
O3—Sawdust diversion	213,300	203,143	193,470	184,257	175,483	167,127	923,480
O4—PP waste diversion	42,160	40,152	38,240	36,419	34,685	33,033	182,529
O5—Employment creation	36,000	34,286	32,653	31,098	29,617	28,207	155,861
O6—Skill development *	19,440	18,514	15,860	13,586	11,640	9971	69,571
O7—Carbon sequestration *	3522	3354	2874	2463	2111	1809	12,611
O8—Compliance-risk reduction *	55,860	53,200	45,600	39,085	33,501	28,715	200,101
O9—Knowledge generation *	128,000	121,905	104,490	89,563	76,768	65,801	458,527
Total	1,427,532	1,359,553	1,276,043	1,199,191	1,128,300	1,062,754	6,025,841

Noted: * Drop-off applied according to Table 13 assumptions. Discount rate = 5% per annum.

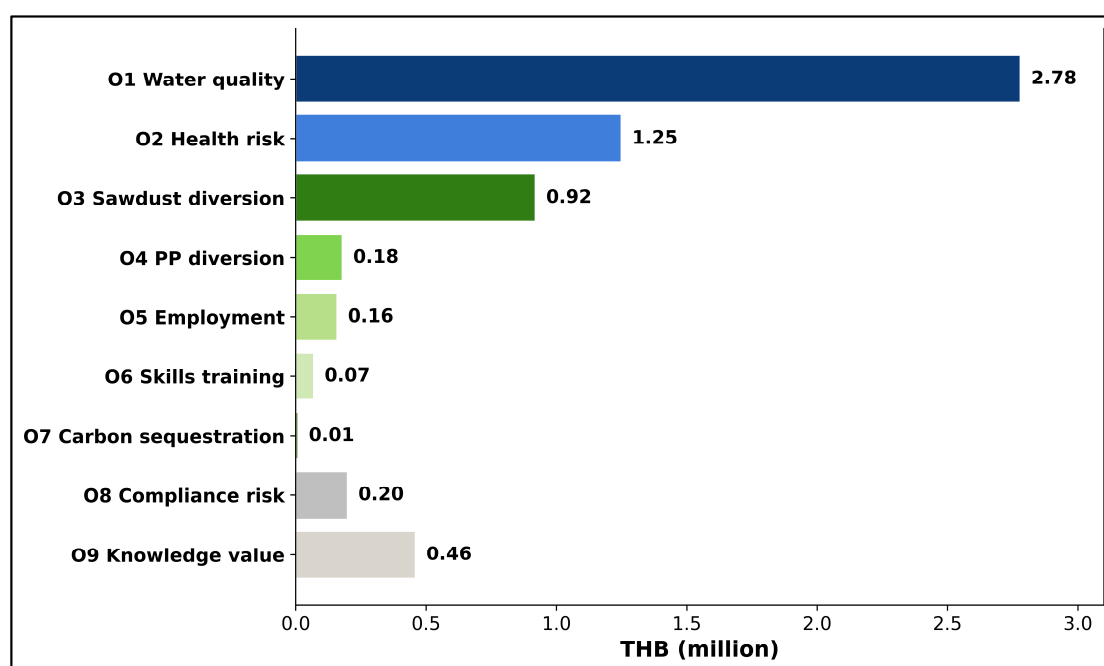
**Figure 7.** Present value contribution of individual outcomes (O1–O9) over the five-year assessment period.

Table 15. SROI ratio calculation and sensitivity analysis.

Scenario	Total PV Outcomes (THB)	Total Investment (THB)	SROI Ratio
Base-case (all outcomes, 5% discount rate)	6,025,841	4,342,000	1.39:1
Conservative (excluding O9: knowledge value)	5,567,314	4,342,000	1.28:1
Conservative (10% discount rate)	4,892,000	4,342,000	1.13:1
Optimistic (full O1 proxy value retained)	6,570,000	4,342,000	1.51:1
Environmental outcomes only (O3 + O4 + O7)	1,118,620	4,342,000	0.26:1
Social outcomes only (O1 + O2 + O5 + O6)	4,248,594	4,342,000	0.98:1

Note: SROI = Total present value of outcomes ÷ total investment. Total investment was revised to 4,342,000 THB according to the updated operating costs assumptions presented in Table 10.

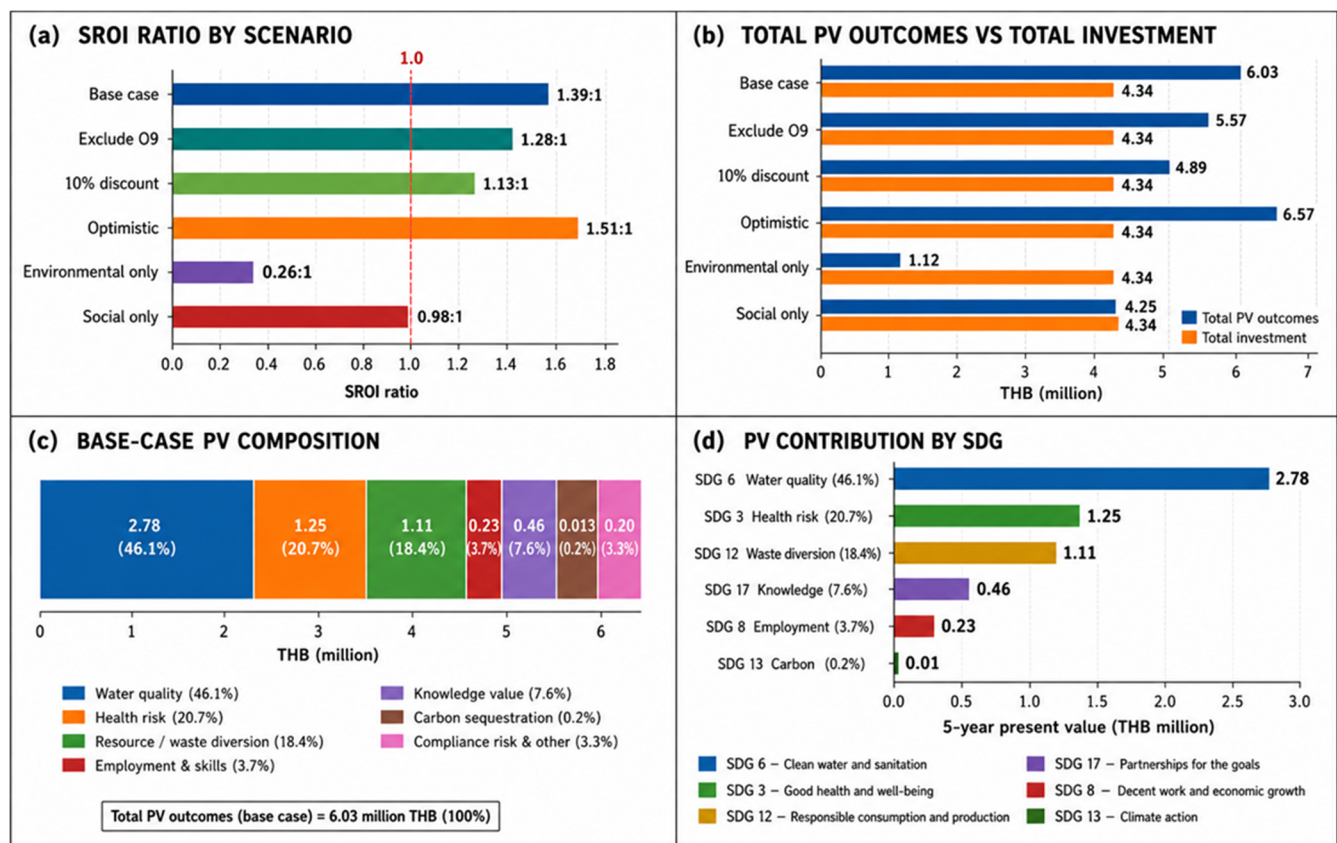


Figure 8. Social return on investment (SROI) assessment of community-scale SPB-500 deployment: (a) SROI ratio under different scenarios; (b) comparison of total present value outcomes and total investment; (c) composition of base-case present value outcomes; and (d) contribution of outcomes to the United Nations Sustainable Development Goals (SDGs).

According to Figure 8b, the overall PV of all outcomes exceeded the overall investment in all cases analyzed, suggesting a positive social return throughout the evaluation period. In the revised case scenario, the overall five-year PV of all outcomes reached 6,025,841 THB against the overall investment of 4,342,000 THB, resulting in an SROI ratio of 1.39:1 in the base-case scenario. Even with conservative assumptions, the social return on investment remained positive (>1.0), providing further evidence that the deployment of SPB-500 at the community level would generate overall social and environmental value. Figure 8c

presents the breakdown of the total PV of the base-case scenario. Improvements in water quality (O1) continued dominating the total PV (46.1%; 2.78 million THB), followed by reduction in health risks (O2) that contributed 20.7% of the total PV (1.25 million THB). Taken together, public health benefits (O1 and O2) provided 66.8% of the overall PV created by the deployment of SPB-500 in the community. Credit-adjusted net GHG balance under the evaluated scenario related to waste diversion and circular resource utilization (O3 + O4) accounted for 18.4% of the total social value created (1.11 million THB). In addition, further contributions were made to social value creation through knowledge generation (O9; 7.6%; 0.46 million THB), skill development and employment creation (O5 + O6; 3.7%; 0.23 million THB), reduction in compliance risks (O8; 3.3%; 0.20 million THB), and carbon sequestration (O7; 0.2%; 0.01 million THB). As evidenced by the findings, social value creation occurred in a variety of outcome categories instead of relying on one single category. However, improvements in water quality and public health clearly stood out as the main factors of social return. Carbon sequestration (O7) made the smallest contribution to the total PV in this case scenario. This finding can be attributed to the relatively low cost of carbon credits in Thailand as opposed to any limitations in the capacity of SPB-500 for carbon storage. Finally, Figure 8d provides information on the contribution of project benefits to the realization of the United Nations Sustainable Development Goals (UN SDGs). SDG 6 (clean water and sanitation) received the largest share (46.1%) of the total social value, followed by SDG 3 (good health and well-being) with 20.7% and SDG 12 (responsible consumption and production) with 18.4% as a result of environmental outcomes. Additional contribution to the achievement of UN SDGs was observed for SDG 17 (partnerships for the goals) with 7.6%, SDG 8 (decent work and economic growth) with 3.7%, and SDG 13 (climate action) with 0.2%. Despite the small monetary value of SDG 13, this can be mostly explained by the relatively low price of carbon credits in Thailand.

4. Conclusions

This study undertakes a holistic sustainability analysis of community-scale co-pyrolysis of sawdust and non-recyclable polypropylene for the production of SPB-500 adsorbent, by performing techno-economic analysis, environmental screening, greenhouse-gas emission calculation, and SROI evaluation within a single analytical framework. The results suggest that co-pyrolysis of sawdust and PP waste at 500 °C has the capability to address waste valorization, environmental protection, and socioeconomic benefits simultaneously. From the results of the techno-economic analysis, it can be concluded that the production of SPB-500 can be realized using a custom-designed LPG-fired pyrolysis unit with a relatively low initial capital cost of 46,000 THB (1286 USD) and an operational cost of 316 THB kg^{−1} (8.8 USD kg^{−1}) at a biochar yield of about 35% (*w/w*). This level of production cost makes SPB-500 competitive compared to the market price of activated carbons due to its low cost. Moreover, the scenario-based techno-economic analysis indicates a short, estimated payback period under the assumed production capacity and selling price, suggesting favorable economic potential for future community-scale implementation. However, these results represent screening-level estimates and should be validated through pilot-scale operation and detailed financial analyses before commercialization. The environmental screening of SPB-500 shows the total gate-to-gate emissions of 8.771 kg CO₂e per kg SPB-500 with the highest contribution from the LPG combustion stage. In addition, when taking into account the benefits of stable C sequestration and waste diversion in the consequential scenario analysis, the total carbon dioxide-equivalent emissions reduce to 3.082 kg CO₂e per kg SPB-500. Compared to activated carbon production process, SPB-500 production has lower energy demand and less environmental impacts due to the avoidance of chemical activation. Social return on investment analysis gives a ratio of 1.39:1 and five-

year NPV of 6.03 million THB. Therefore, it can be argued that social- and credit-adjusted net GHG balance under the evaluated scenario derived from this project outweighs the investment. Environmental health benefits are the largest monetized benefits and constitute more than half of the social value created. These SROI findings should be interpreted based on scenarios because they rely heavily on financial indicators from the literature rather than actual social impact figures obtained through direct engagement with stakeholders. All of the above-described techno-economic, environmental, and social results are associated with uncertainties based on the assumptions made concerning biochar yield, energy use, emission coefficients, the permanence of sequestered carbon, avoidance credits, adsorption dosage, regeneration efficiency, economic parameters such as market value, wage rate, and discount rate, as well as SROI as a social financial proxy. Even though a sensitivity analysis has been carried out for the SROI evaluation, a thorough multi-factorial uncertainty analysis has not yet been undertaken. The reported annual production capacity, techno-economic performance, and SROI outcomes are scenario-based screening estimates intended to evaluate the potential feasibility of community-scale implementation. Experimental validation through pilot-scale operation and detailed engineering design is required before commercial deployment.

In spite of the fact that this study focuses only on gate-to-gate environmental impacts and social valuation based on a five-year period, the conclusions made based on the findings clearly suggest that community-scale co-pyrolysis can be considered a promising approach to valorize problematic waste streams and turn them into value-added products. In particular, future research might be directed towards full-scale piloting, life cycle assessment, use of renewable energy, syngas utilization, and testing the adsorption capacity of SPB-500 under actual operation.

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Abbreviations

The following abbreviations are used in this manuscript:

CAPEX	Capital Expenditure
CED	Cumulative Energy Demand
CHNS	Carbon, Hydrogen, Nitrogen, and Sulfur Analysis
EFC _{seq}	Emission Factor for Carbon Sequestration
EF _{elec}	Electricity Emission Factor
EF _{LPG}	Liquefied Petroleum Gas Emission Factor
EF _{PP}	Emission Factor for Polypropylene Open Burning
EF _{saw}	Emission Factor for Sawdust Landfill Decomposition
EOL	End-of-Life
FEP	Freshwater Eutrophication Potential
FTE	Full-Time Equivalent
GAC	Granular-Activated Carbon
GHG	Greenhouse Gas
GWP100	Global Warming Potential (100-year time horizon)
HTP	Human-Toxicity Potential
IBI	International Biochar Initiative
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LPG	Liquefied Petroleum Gas
MJ	Megajoule
OPEX	Operating Expenditure
PAC	Powdered-Activated Carbon
PCD	Pollution Control Department
PID	Proportional–Integral–Derivative Controller
PP	Polypropylene
PV	Present Value
SDG	Sustainable Development Goal
SPB	Sawdust–Polypropylene Biochar
SPB-500	Sawdust–Polypropylene Biochar Produced at 500 °C
SROI	Social Return on Investment
TEA	Techno-Economic Analysis
TGO	Thailand Greenhouse-Gas Management Organization
THB	Thai Baht
TIC-101	Temperature Indicator Controller
UN	United Nations
USD	United States Dollar
WHO	World Health Organization

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