


Production of a nutrient enriched biochar: a techno-economic feasibility analysis

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Abstract: A techno-economic feasibility analysis was conducted for a biomass pyrolysis plant that utilized Eucalyptus to produce fertilizer-enriched biochar. Key parameters – biomass throughput, fertilizer loading, and selling price – were optimized for financial viability using net present value (NPV), internal rate of return (IRR), return on investment (ROI), and payback period (PP). Four case scenarios were assessed, focusing on energy and co-product utilization, particularly pyrolysis oil for herbicide production and synthesis gas for electricity generation. Results show that Scenario 2 (electricity generation from synthesis gas and wood vinegar combustion, with separate sale of the phenolic fraction) and Scenario 4 (separate sale of both wood vinegar and phenolic fractions) may be profitable, though their low IRR (1.1%) could deter investment. Optimization indicated that increasing biomass feed rates and reducing the fertilizer-to-biomass ratio may enhance economic outcomes. However, the high cost of enriched biochar relative to conventional fertilizers poses a significant challenge to both short- and long-term economic feasibility. These findings underscore the need for innovative strategies to improve the economic viability of biochar and to support its adoption among agricultural stakeholders. © 2025 The Author(s). *Biofuels, Bioproducts and Biorefining* published by Society of Industrial Chemistry and John Wiley & Sons Ltd.

Key words: catalytic pyrolysis; techno-economic feasibility analysis; biochar; fertilizer

Introduction

Biochar has been utilized for thousands of years for heating and agriculture. Indigenous tribes in the Amazon employed biochar as a method of enriching soil, producing *terra preta* – a dark colored, well-drained, less acidic, and nutrient-rich soil that is more fertile than native soils.¹ Biochar is formed by pyrolysis, a thermal process that transforms lignocellulosic biomass into high-value products, typically from 200 °C to 700 °C in an oxygen-depleted

environment.² Biochar applications improve soil quality by increasing crop growth rates, enhancing soil structure for better drainage and aeration, and providing a favorable environment for mycorrhizal fungi and other beneficial microbiota.³

Current agricultural practices using synthetically produced fertilizers, diminish biodiversity (e.g., through soil degradation, preference for specific plant species, and promotion of monocultures) and degrade water quality. The levels of fertilizing agents such as nitrogen, in both surface and groundwater, have been increasing steadily to levels

exceeding safe limits.⁴ Excess fertilizers are transported by rain and snowmelt into water sources, resulting in nitrogen leaching, contamination, and eutrophication. Furthermore, surplus nitrogen can lead to soil acidification and deplete micronutrients, which severely impacts crop growth and yield.⁵ Other findings have linked excess nitrogen to reduced soil fertility, which compromises overall soil health.

A review of the literature highlights conflicting perspectives on the potential of biochar in enhancing soil fertility and crop yields. Some authors state that biochar is a relatively economic soil additive and they allude to possible benefits relating to soil health and increased crop yield.^{6,7} Others are more cautious, citing high levels of uncertainty regarding biochar production costs and market biochar prices as key concerns.^{8–10} Biochar, although beneficial, is not in itself a traditional fertilizer: it functions as a soil amendment, enhancing soil properties and fertility. However, previous studies primarily evaluate biochar as a standalone soil amendment rather than exploring its integration with fertilizers in an optimized pyrolysis process. This study addresses this gap by systematically evaluating the economic viability of nutrient-enriched biochar as a replacement/supplement for the neat fertilizers that are currently used.

The high surface area and porosity of biochar facilitate the adsorption and controlled release of nutrients, making nutrient-enriched biochar a promising slow-release fertilizer. The application of nutrient-enhanced biochar to soils has also been associated with increased fertility, decreased reliance on synthetic fertilizer supplementation, and promotion of sustainable farming by recycling nutrients from nutrient-containing waste resources.¹¹

This study therefore assessed the economic feasibility of introducing nitrogen, phosphorus, and potassium (NPK) fertilizing agents during pyrolysis for the supplementation of endogenous inorganic salts of biochar to yield nutrient-enriched biochar. To enhance the comprehensiveness of the analysis, four distinct scenarios for the valorization of pyrolysis co-products were considered with varying implications for energy recovery, chemical extraction, and financial viability. These scenarios provided a formal structure for assessing the financial performance and choosing the most financially appealing scenario.

As the pyrolysis of biomass is associated with the co-synthesis of value-added pyrolytic fluids (*i.e.*, pyrolysis oil and syngas), offset scenarios were explored. Pyrolysis oil can be utilized as both an energy intermediate for heat or power generation and through its fractionation into various platform chemicals. The two primary fractions of pyrolysis oil were considered, namely wood vinegar, which is typically used as an herbicide/pesticide,^{12,13} and a phenolic fraction,

which is used as an antiseptic and as a reagent in synthetic plastic.¹⁴ The utilization of syngas was only considered for heat and power generation.

From the preliminary analysis, four optimization methods were implemented to further optimize profitability and scalability. The optimizations focused on varying the yield of biochar, changing the fertilizing agent ratios, selling price optimization, and determining the impact of mark-up strategies. Employing these changes, the study aimed to identify conditions under which nutrient-enriched biochar production can be an economically viable and scalable solution for sustainable farming.

Methods

The techniques used in this study attempted to evaluate the economic feasibility of nutrient-enriched biochar production methodically. Scenario-based evaluation, financial modeling, and optimization were integrated to enhance the assessment of investment profitability and viability. Computational software was employed to automate calculations and ensure consistency in cost and financial estimates. Key industry parameters were incorporated to provide a comprehensive evaluation with proper balancing of production costs and likely returns.

Analysis description

The techno-economic feasibility analysis was undertaken using a combination of Microsoft Excel and Python, facilitating routine computations and simulations. The *xlwings* Python library was utilized to facilitate automation and manipulation across Excel Spreadsheets and Python. The process variables of optimization used to enhance the financial indicators included daily biomass throughput, fertilizer loading, biochar yield, fertilizer agents' ratio, and selling price of co-products.

The financial performance of the plant was assessed using key financial indicators that inform investors and financial managers of a project's profitability (Table 1), namely the net present value (NPV), internal rate of return (IRR), return on investment (ROI), and payback period (PP).¹⁵ The plant was assumed to be constructed within 1 year, during which plant performance is set to 0% as building, installation and commissioning occur. Plant performance during commissioning in the second year was set at 75% – this period accommodates operational fine-tuning and optimization. Thereafter, the process and equipment were assumed to have matured such that the plant achieved 100% performance. The plant's lifespan was set to 20 years for all scenarios. The 2023 average exchange rate of the US

Table 1. Performance indicators used for the feasibility analysis.

Performance indicator	Short form	Description
Net present value	NPV	Financial metric used to estimate the present value of future cash inflows, considering the inflows and outflows in terms of time value inflows
Internal rate of return	IRR	A financial indicator that gives the discount rate at which the net present value of future inflows and outflows becomes zero
Return on investment	ROI	Financial ratio useful in calculating the profitability of a given investment using net profit and cost of investment
Payback period	PP	The recovery period of the initial cost of investment based on expected cash inflows

Dollar (\$) to the South African Rand (ZAR) was set at \$1 = R 18.4435 for the analysis. The electricity selling price of R2.80 per kWh (\$0.15 per kWh) was acquired from the National Energy Regulator of South Africa (NERSA) for agricultural use. Electricity selling prices and other monetary variables were projected to increase annually at a rate of 6%, aligned with South Africa's historical inflation rate.¹⁶ This approach ensured consistency across financial projections while maintaining realistic market assumptions.

Fertilizing agents and constant parameters

Using a previous assay of various prospective fertilizing agents suitable for *in-situ* nutrient-loaded biochar synthesis,¹⁷ K₂CO₃, K₃PO₄, and Ca(NO₃)₂·4H₂O were chosen to represent K, P, and N fertilizers, respectively. The fertilizing agents were introduced in a 1:1:1 mass ratio. Due to their niche applications, readily available bulk prices of these fertilizing agents were difficult to source. Instead, bulk prices for urea, diammonium phosphate (DAP), and muriate of potash (MOP) were used as approximations. The most commonly used N fertilizer is usually prilled urea.¹⁸ Diammonium phosphate is a highly soluble source of fertilizer containing mostly P.¹⁹ Muriate of potash is the most common form of potash and it contains a minimum of 60% K₂O.¹⁸ The prices in Table 2 were averaged over a 10-year period from April 2012 to April 2022 based on World Bank data.²⁰ The parameters depicted in Table 2 were set to constant values for the entire analysis. The biomass processing rate of 10000 kg per day, as stated in Table 3, was measured on a neat moisture basis (35%) before drying to 8% moisture, as shown in Figs 1–4. This feed rate also included 10% NPK fertilizers, contributing to the total input load. The energy efficiency, η_{energy} , was calculated by Eqn (1). E_{gen} is the

Table 2. Constant parameters of analysis.

Parameter	Value	Unit
Operation period per annum		
Daily operating hours	24	h day ⁻¹
Operating period	92	% a ⁻¹
Planned maintenance	4	% a ⁻¹
Unplanned maintenance	4	% a ⁻¹
Yearly inflation ¹⁶	6	% a ⁻¹
Biomass parameters		
Neat moisture content ³⁶	35.5	%
Ash content ¹⁷	1	%
Dried moisture content ¹⁷	8	%
Costing of feedstock		
<i>Eucalyptus grandis</i> ^{25–30}	30	\$ ton ⁻¹
Urea ²⁰	350	\$ ton ⁻¹
DAP ²⁰	174	\$ ton ⁻¹
MOP ²⁰	331	\$ ton ⁻¹
Fuel to energy: internal		
Electricity selling price ³⁷	0.15	\$ kWh ⁻¹
Energy efficiency	29	%

Table 3. First iteration parameters for analysis.

Parameter	Value	Unit
Feed rate (including fertilizing agents)	10 000	kg day ⁻¹
Fertilizer loading	10	%
Fertilizing compound loading ratio	1:1:1	–
Liquid yield	0.45	%
Water contained in liquid	0.15	%
Biochar yield	0.4	%
Noncondensable gas yield	0.15	%
Average biochar price: bulk	1.09	\$ kg ⁻¹
Average biochar price: niche	6.00	\$ kg ⁻¹
Sales ratio, biochar niche	10	%
Sales ratio, biochar bulk	90	%
Markup on fertilizer	75	%

energy density of diesel in kWh kg⁻¹ at 65% to 70% loading and HHV_{diesel} is the higher heating value of diesel:

$$\eta_{\text{energy}} = \frac{E_{\text{gen}}}{\text{HHV}_{\text{diesel}}} \quad (1)$$

Scenario description

An initial iteration was conducted to evaluate different pyrolysis valorization strategies and to establish the most

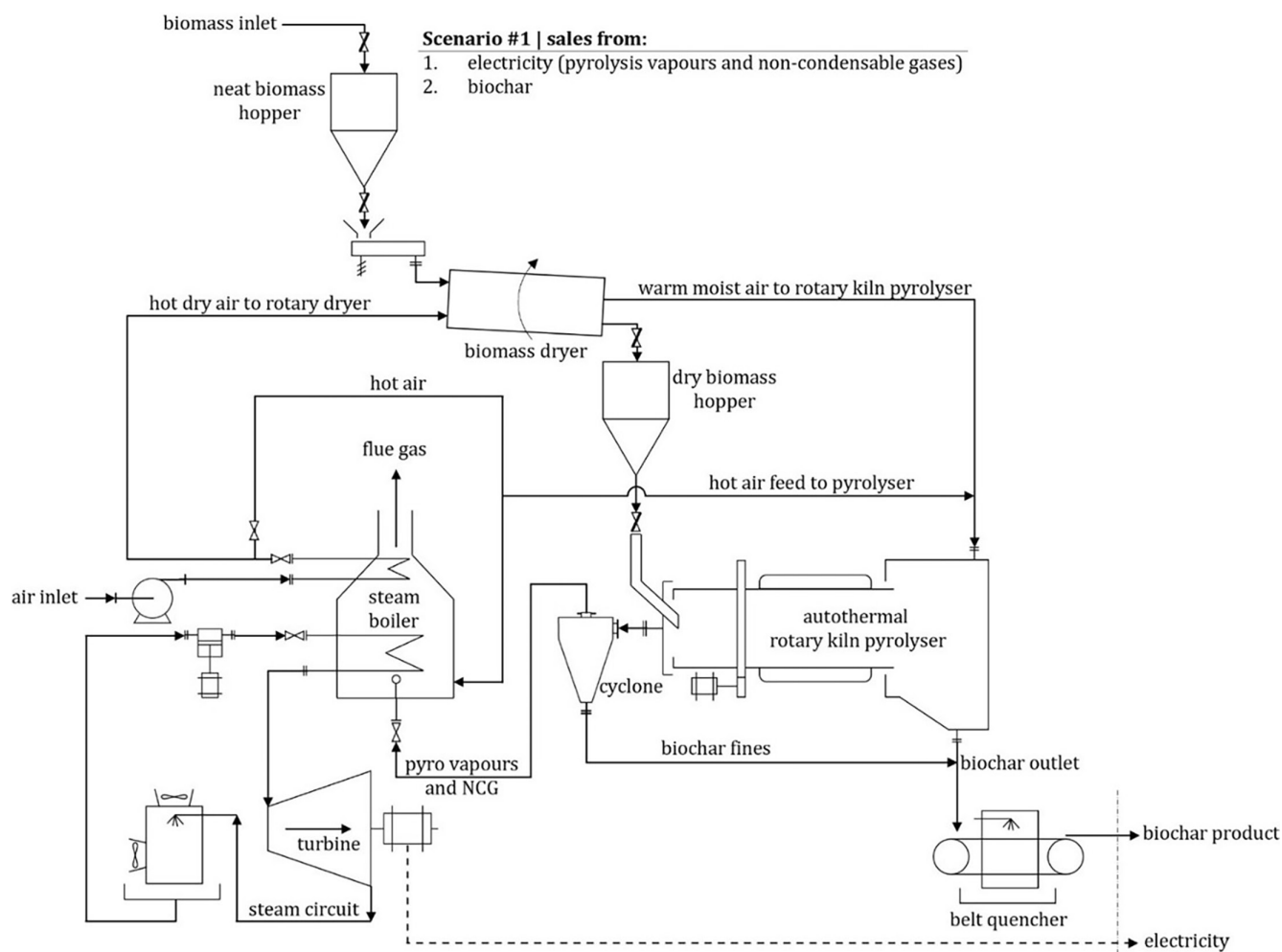


Figure 1. Schematic of Scenario 1.

economically viable approach. The four scenarios employed in this economic assessment are as follows (Figs 1–4):

1. selling electricity to the grid from combusting both synthesis gas and all pyrolysis oil (wood vinegar and phenolic fraction);
2. selling electricity generated from the combustion of synthesis gas and wood vinegar, and extracting and separately selling the phenolic fraction;
3. selling all pyrolysis oil as wood vinegar; and
4. extraction and separate selling of wood vinegar and phenolic fractions.

In Scenarios 3 and 4, synthesis gas is not utilized to generate electricity. Both of these scenarios focus exclusively on optimizing the commercialization of pyrolysis oil fractions – either selling all oil as wood vinegar (Scenario 3) or separating and selling both wood vinegar and phenolic fractions (Scenario 4). In contrast, Scenarios 1 and 2

incorporate syngas combustion to generate electricity, which provides an additional revenue stream but reduces the availability of pyrolysis oil for commercial sale. Each scenario represents a distinct strategy for utilizing pyrolysis by-products, impacting financial performance through different revenue streams. Despite the complexity and lack of industrial-established phenolic extraction processes, this option was nonetheless considered as a hypothetical case study in anticipation of future technological advancements.

Optimization strategy

Following the examination of four pyrolysis valorization alternatives, further improvements were developed to achieve financial viability. The first techno-economic analysis established key limitations – such as high fertilizer costs, long payback periods, and suboptimal biochar yields – which negatively impacted investor appeal and project viability. To address these limitations, a systematic optimization

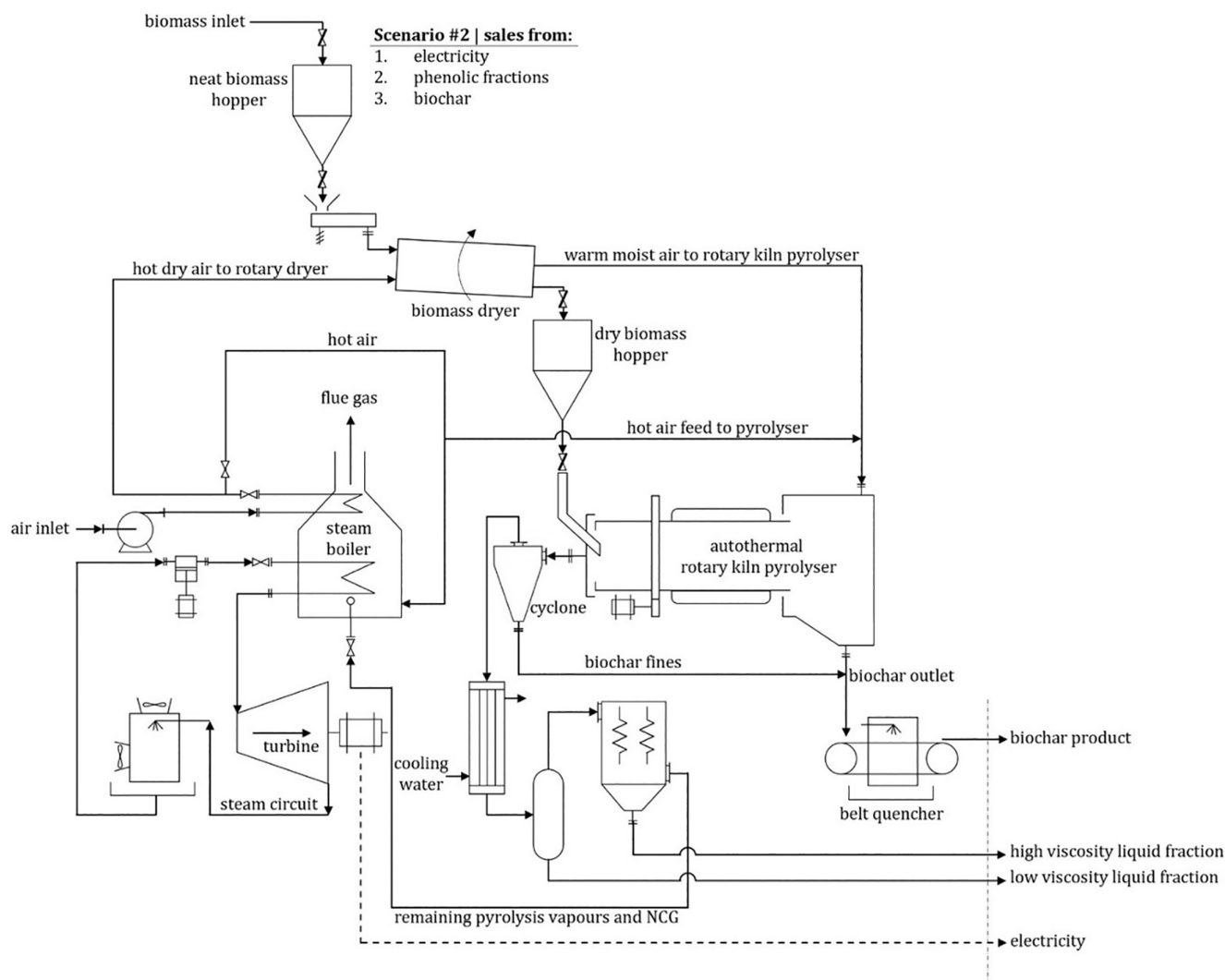


Figure 2. Schematic of Scenario 2.

framework was developed, optimizing process conditions and economic inputs. Four optimization strategies were developed to improve investment viability.

Feed rate optimization

For the first optimization method, the pyrolysis yields, the average biochar price for both bulk and niche applications, as well as the mark-up on fertilizing agents were kept constant (Table 3). The feed rate was iterated between 1 kg day^{-1} and $50000 \text{ kg day}^{-1}$ to find the optimal feed rate.

Enriched biochar yield optimization

The enriched biochar yield was varied from 10% to 60%, and the feed rate was fixed at $50000 \text{ kg day}^{-1}$. Factors such as heating rate, temperature, pressure, and holdup time have

been found to impact the final yield.^{21–23} Low-temperature pyrolysis (torrefaction) occurs below $400 \text{ }^\circ\text{C}$, producing mostly char, with structural changes starting as low as $275 \text{ }^\circ\text{C}$.²⁴ The model also considers synthesis gas combustion and potential sale of pyrolysis oil. High biochar yields result in minimal volatile fractions, which can create challenges in post-pyrolysis processing of pyrolysis oil and gas.²³ The biochar yield was iterated between $0.1 \text{ kg}_{\text{biochar}} \text{ kg}_{\text{feed}}^{-1}$ and $0.6 \text{ kg}_{\text{biochar}} \text{ kg}_{\text{feed}}^{-1}$, and the feed rate was fixed at $50000 \text{ kg day}^{-1}$.

Fertilizer ratio optimization

This section introduces more realistic ratios of the fertilizing agents, ignoring the mass of other elements contributing to the total mass (oxygen, carbon, etc.). Mass fractions for N, P, and K were calculated using Eqn (2):

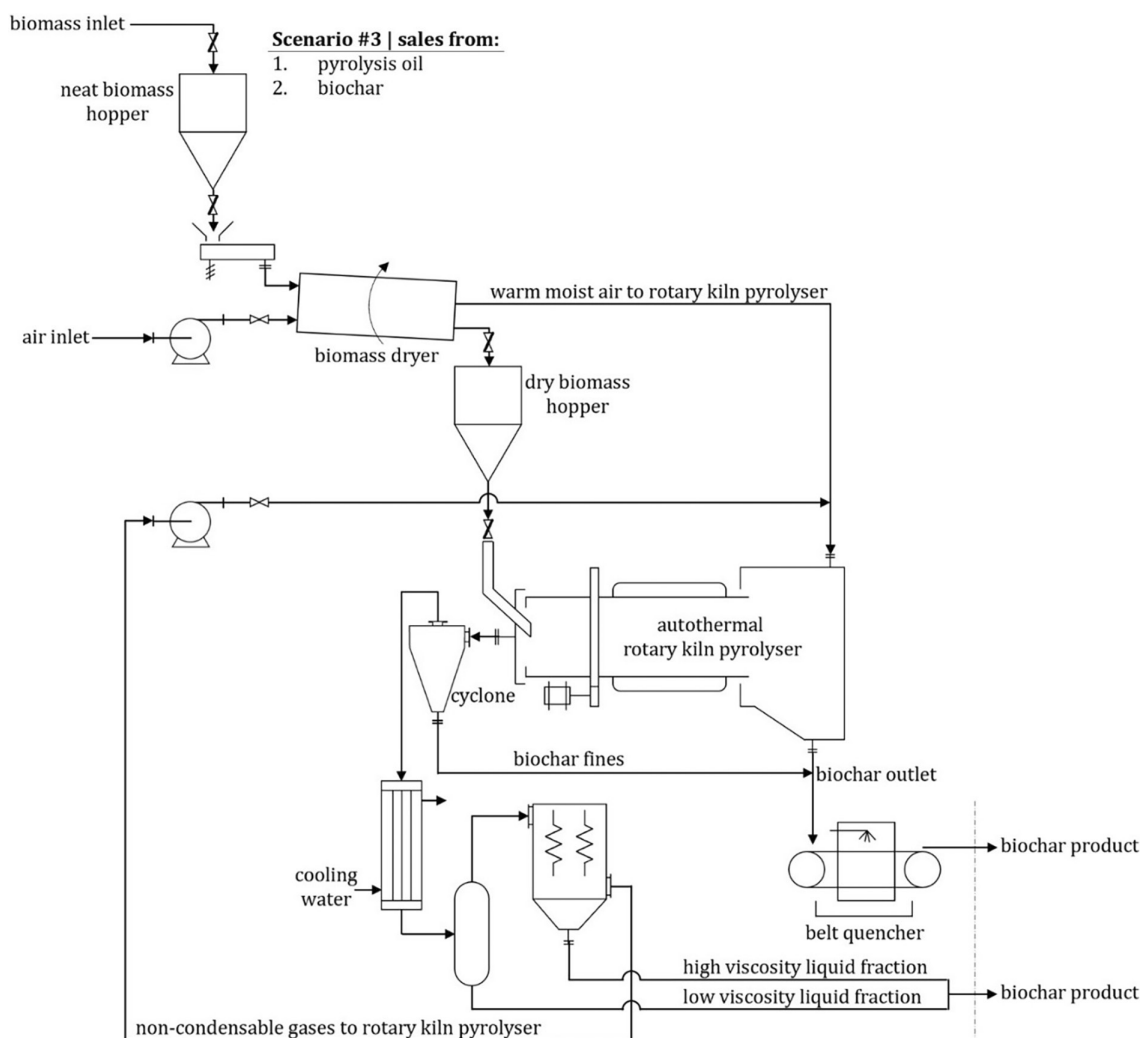


Figure 3. Schematic of Scenario 3.

$$\omega_i = \frac{n_i M_i}{M_{\text{compound}}} \quad (2)$$

where i represents N, P, or K, ω_i denotes the mass fraction of element i , M_i represents the molecular mass of element i , and M_{compound} represents the evaluated molecular mass of the compound.

Anhydrous calcium nitrate ($\text{Ca}[\text{NO}_3]_2$) was used to represent N, excluding bound water of crystallization, and potassium phosphate (K_3PO_4) was chosen to represent P, despite it containing three times more K than P, as it is more thermally stable than other choices.¹⁷

Selling price optimization

The key variables that were optimized in this subsection comprised the biochar selling price and the markup on fertilizer. For the initial iteration, biochar was priced at \$1.09

and \$6.00 per kg for bulk and niche applications, respectively, with a niche:bulk ratio of 10%. The biochar selling price and the markup on the fertilizing agents were iterated to produce an enriched biochar selling price between \$0.01 and \$1.36 per kg.

Growing *Eucalyptus*

The major factors for the economic feasibility of planting *Eucalyptus* from seed include seeding costs, fertilization, pesticides, cultivation practices, maintenance, and harvesting. An analysis was conducted on six studies, with adjustments made for inflation to ensure comparability.^{25–30} In Brazil, plantations of *Eucalyptus* for pulp production were examined, excluding land acquisition costs, for comparison.²⁶ Over 7 years, the total expenditure amounted to \$4 746.70 per hectare, whereas the selling price ranged from \$14.93 to \$43.73 per ton. In Kenya, *Eucalyptus grandis* plantations

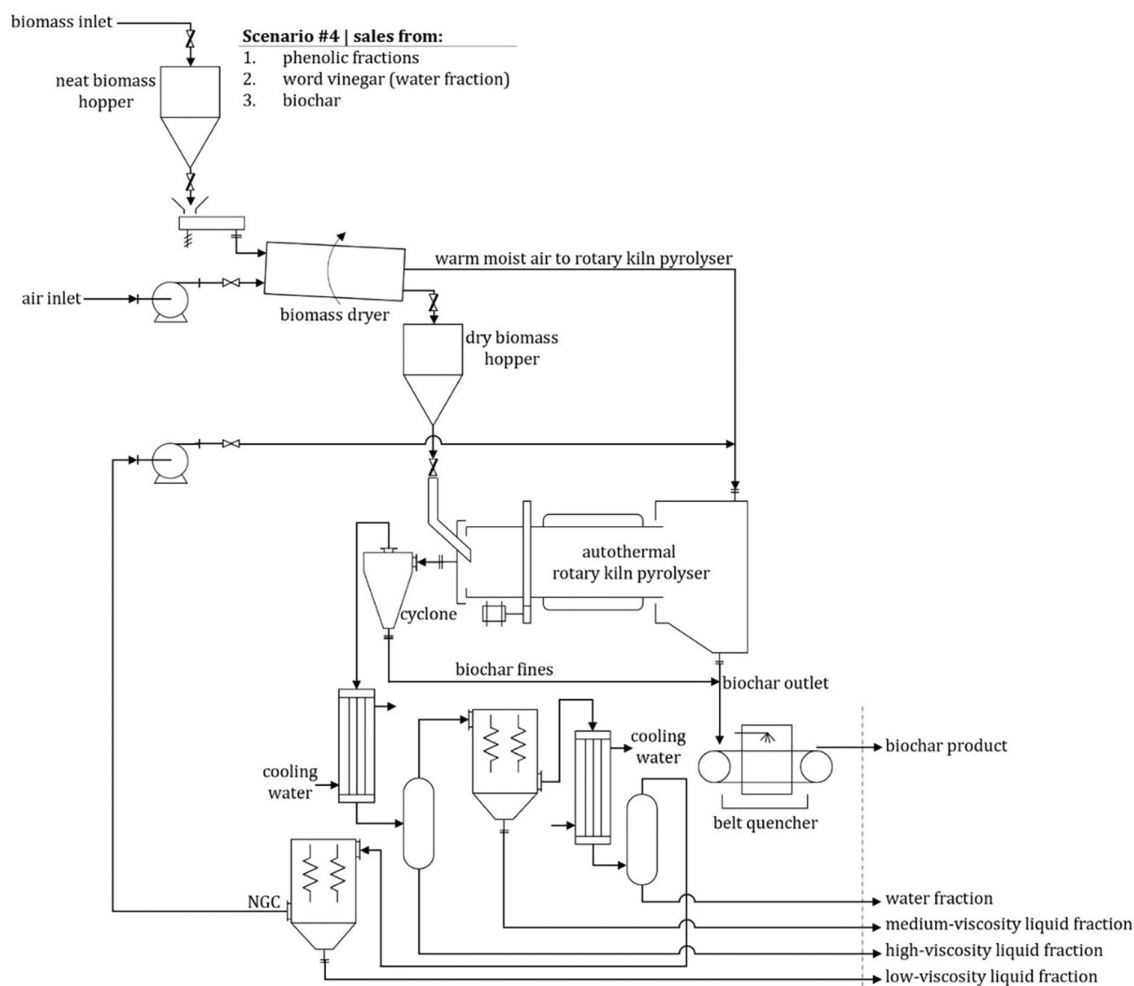


Figure 4. Schematic of Scenario 4.

were assessed for transmission poles and firewood, with a cumulative 10-year cost of \$3469.67 per hectare. At an internal rate of return of 5.2%, the estimated selling price varied between \$29.15 and \$43.73 per ton.²⁷ In Laos, monoculture plantations of *Eucalyptus* were studied, revealing a total cost of \$5 715.49 per hectare over 7 years and a selling price from \$74.63 to \$111.95 per ton – significantly higher than other studies.²⁹ Further insights confirm that the average cost of \$30 per ton for *E. grandis* is consistent with the majority of reviewed studies.^{25,28,30} Fig. 5 highlights the cost price per ton of harvested *Eucalyptus* across various studies.

Project evaluation metrics

The parameters outlined in Table 3 were used for an initial iteration in the cost estimation process and were optimized using the *xlwings* library within Jupyter Notebook. The project evaluation metrics (equipment bill, fixed capital investment, working capital, production costs, etc.) were

calculated to illustrate the results for this specific iteration of parameters (Table 3).

Equipment bill

The equipment bill was based on and adapted from a previous study.³¹ The techno-economic feasibility study accounted for the variation in the cost of constructing process plants in the chemical and manufacturing industries, using the 2023 Chemical Engineering Plant Cost Indices (CEPCIs). The six-tenths rule was also applied as a reasonable approach¹⁵ as access to more specific cost data for specific equipment and operations is limited, with a sizing factor included in the equation below, where *FR* is the feed rate and *SF* is the sizing factor:

$$\text{\$ Cost (2023)} = \frac{\text{CEPCI}_{2023}}{\text{CEPCI}_{2010}} \times \text{\$ Cost (2010)} \times \left(\frac{FR}{SF} \right)^{0.6} \quad (3)$$

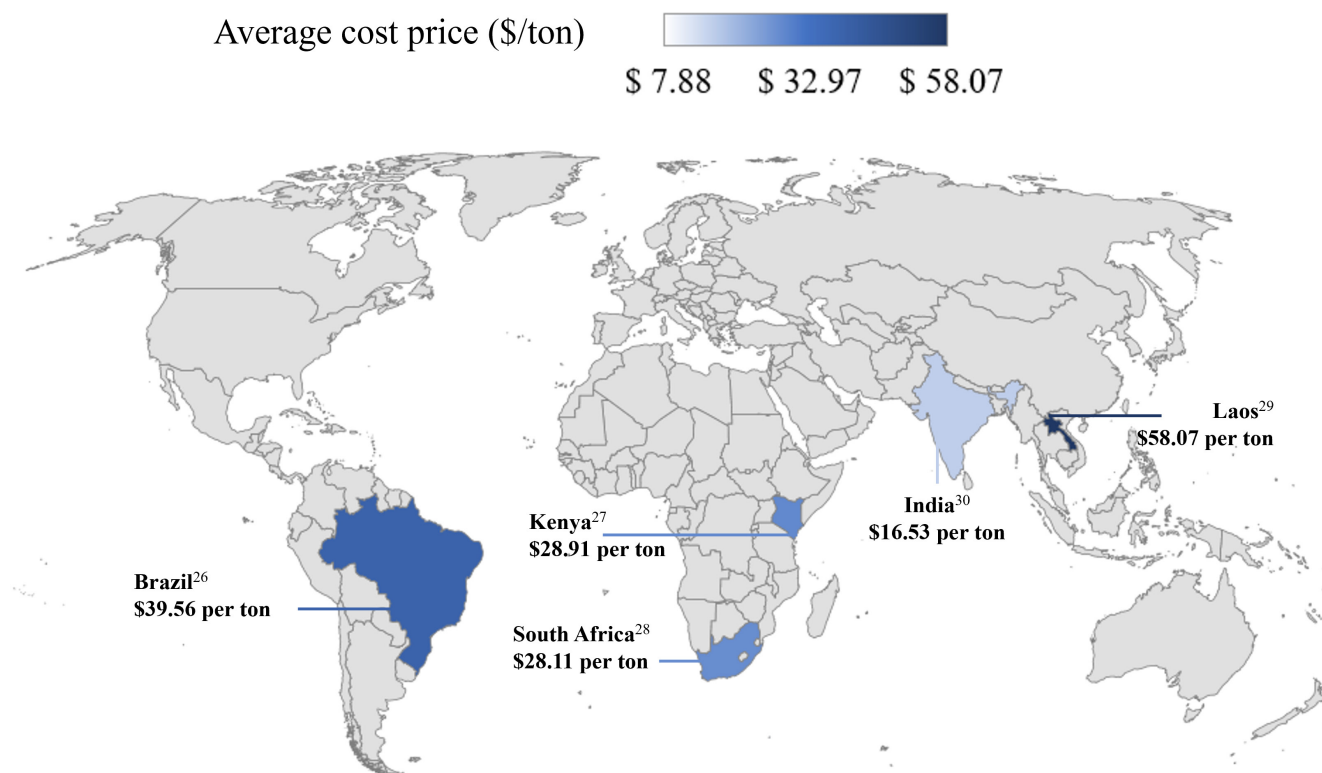


Figure 5. Cost price of harvested *Eucalyptus* from around the world.

Table 4. Chemical engineering plant cost indices 2010 and 2023.

Chemical Engineering Plant Cost Indices (CEPCI) classification	2010	2023
General CEPCI	556.3	789.6
Equipment	667.5	990.5
Heat exchangers and tanks	617.8	803.2
Process machinery	627.0	1016.3
Pipes, valves and fittings	840.2	1330.7
Process instruments	426.0	565.5
Pumps and compressors	902.0	1484.2
Electrical equipment	484.7	807.2
Structural supports and miscellaneous	689.6	1095.1
Construction labor	331.0	374.7
Buildings	503.3	799.1
Engineering and supervision	336.6	315

The CEPCI values were sourced from the Chemical Engineering Plant Cost Index for 2023,³² and are reproduced in Table 4, and the equipment bill is shown in Table 5. The total fixed cost includes only pyrolysis-relevant equipment; all of the pretreatment equipment along with wet sawdust hopper are excluded.

Fixed capital investment

The upfront costs for long-term assets such as equipment and piping in plant construction were represented by the critical financial metric of fixed capital investment (FCI). Proper evaluation of FCI is essential for determining a project's return on investment, payback period, and feasibility.³³ The FCI calculations for chemical processing plants, include equipment costs, additional materials costs, additional general costs, as well as contingencies³¹ (Table 6).

Working capital

Working capital represents the additional funds required beyond the fixed capital investment for initiating and sustaining operations until the plant reaches profitability,¹⁵ and the key factors included:

- cost of purchasing 1 month's *E. grandis* and fertilizing agents;
- cost of 1 month's raw material in-process;
- cost of producing half a month's output;
- outstanding accounts for 1 month; and
- petty cash reserves.

The total working capital (\$405 543, Table 7) comprised the cost of unprocessed raw material (\$11 651), the value

Table 5. Equipment bill.

Description	Unit operation	Cost (2010) \$ unit ⁻¹	Cost (2023) \$ unit ⁻¹
Wood chipper	Pretreatment	302 200	17 856
Cutting mill	Pretreatment	302 200	17 856
Biomass chopping screen	Pretreatment	22 500	1 329
Wet sawdust hopper	Storage	41 400	2 446
Rotary dryer	Pretreatment	635 200	40 261
Steam blower	Pretreatment	803 300	47 463
Biomass-to-pyrolyzer screw feeder	Pyrolysis	163 500	9 601
Dry sawdust hopper	Storage	42 000	2 446
Pyrolysis fluidized bed reactor	Pyrolysis	836 000	49 395
Pyrolysis vapor cyclone	Separation	1 216 760	74 566
Non-condensable gas-liquid separation	Separation	1 021 860	12 727
Electrostatic precipitator	Separation	292 400	17 277
Pyrolysis oil condenser	Separation	1 016 760	59 009
Water pump	Separation	669 700	39 569
Fluidized bed sand hopper	Separation	41 400	2 446
Combustion-pyrolysis screw feeder	Combustion	379 600	22 429
Combustion fluidized bed	Combustion	234 300	14 435
Air preheater	Combustion	2 543 600	150 290
Combustion gas blower	Combustion	62 200	3 675
Combustion vapor cyclones	Combustion	1 104 700	65 272
Flue gas blower	Combustion	214 700	12 686
Cooling tower	Cooling	3 005 100	177 557
Fuel storage	Storage	24 300	2 872
Liquid fuel pump	Storage	24 300	1 436
Total equipment cost		14 275 300	844 897
Total fixed capital cost		12 122 300	717 687

of processed raw material (\$146 297), production costs (\$77 998), accounts receivable from sales (\$146 297), and petty cash (\$23 301). The total capital investment, which combines fixed capital investment and working capital, amounted to \$3 456 838 for this iteration.

Production costs

The costs of producing a product may be broadly classified into two categories: production costs, and general costs. Production costs are further subdivided into direct production costs (*i.e.*, costs directly associated with the production rate), fixed production costs (*i.e.*, costs associated with local taxation, insurance, and depreciation, the latter by the straight-line method based on a 20-year plant lifespan), and plant overheads.¹⁵ Estimates for plant overheads (*i.e.*, engineering services, bonuses, security, and workshops) were set at 50% of the sum of labor, supervision, and maintenance costs (see Table 8 for relevant cost factors, and Table 9 for average values relevant to the moderate case study).

Results and discussion

This section presents the techno-economic analysis results, evaluating financial viability for the four pyrolysis valorization scenarios. Key financial indicators like NPV, IRR, ROI, and payback period were addressed both under baseline analysis as well as optimization tuning. The impact of parameter tuning, such as adjustment to the feed rate and fertilizer ratio, was examined systematically.

Preliminary economic assessment of pyrolysis scenarios

The analysis of the four scenarios defined above reports biochar and fertilizer sales separately (Table 10) to clarify which contributed more towards the financial performance of the enriched biochar production in terms of their impact on the financial indicators of NPV, IRR, ROI, and PP. The feed rate, fertilizer loading rate, and markup remained unchanged across the iterations with selling and cost prices remaining the same for enriched biochar. The total purchase cost of the feedstock was \$0.90 kg⁻¹, where fertilizer agents and *E. grandis* contributed \$0.89 and \$0.01 kg⁻¹, respectively. The enriched biochar was priced at \$1.58 kg⁻¹ with the fertilizer agents and biochar contributing \$1.55 and \$1.59 kg⁻¹, respectively. The total markup, including all other expenses, was 86.87%.

To assess the long-term financial viability of these scenarios, a 20-year discounted cash flow analysis was conducted. The results indicate that Scenario 2 and Scenario 4 demonstrated marginal economic feasibility, with IRRs of just 0.3% and 0.2%, respectively, making them unattractive to investors (Table 11). The low IRR implies low returns relative to original capital investments, and hence these opportunities would require additional financial incentives to make

Table 6. Fixed capital investment (FCI) based on a chemical processing plant.

Cost type	Description	Factor	Contribution (\$)	Total (\$)
Equipment cost				844 897
Additional materials		66.20		559 322
	Piping	32.00	270 367	
	Concrete	8.70	75 196	
	Steel	1.70	14 363	
	Instruments (1)	7.30	61 678	
	Electricity	8.30	70 126	
	Instruments (2)	3.40	28 727	
	Paint	0.60	5 069	
Additional costs				1 138 527
	Labor costs	0.36	493 352	
	Indirect costs	0.34	645 174	
Contingencies		0.20		508 549
Fixed capital investment (FCI)				3 051 296

Table 7. Working capital.¹⁵

Item	Cost	Unit
Cost of raw material	11 656	\$ month ⁻¹
1 month's raw material in-process	146 297	\$ month ⁻¹
Product: ½ month feedstock processed	77 998	\$ ½ month ⁻¹
Sales – outstanding accounts	146 297	\$ month ⁻¹
Petty cash	23 301	\$ month ⁻¹
Total working capital	405 543	

them more acceptable. Scenario 1 and Scenario 3 are still more cash-starved, with $-\$2.86$ and $-\$4.26$ million NPVs and -7.3% and -12.2% IRRs, respectively. These reflect long-term financial losses over the lifespan of the project. Scenario 1, with electricity resale back to the grid, stumbles with less-than-expected revenue returns from syngas combustion. Although it starts generating positive cash flow from 24.9 years, this is way beyond the expected investment payback period. Scenario 3, dependent on the sale of all pyrolysis oil as wood vinegar, is associated with a long payback period (48.4 years) and is therefore not feasible due to the 20-year lifespan of the project. Scenario 2 and Scenario 4 offer slightly better financial performance, although their profitability remains insufficient to justify large-scale investment. Given that none of the scenarios provide a compelling financial case for investors, optimization strategies were implemented to explore potential refinements that might enhance feasibility by improving biochar yield, adjusting fertilizer ratios, and optimizing pricing models.

Table 8. Appropriate ranges of costs.¹⁶

Cost type	Range/description
Labor	15% of production costs
Direct supervision	15% of labor costs
Utilities	10% to 20% of production costs
Maintenance	3% to 20% of fixed capital investment (FCI)
Consumables	15% of maintenance costs
Laboratory fees	10% to 20% of labor costs
Patents and royalties	2% to 6% of production costs
Local tax	1% to 2% of FCI
Insurance	1.25% of FCI
Plant overhead costs	50% of labor, supervision, and maintenance costs
Administration costs	40% to 60% of labor costs
Distribution and marketing	2% to 20% of sales income
Research and development	2% of sales costs
Contingency	1% to 5% of total costs

Optimization results

To refine investment feasibility, various optimization strategies were implemented, systematically adjusting process variables and financial parameters. The following subsections analyze the impact of specific optimization strategies on financial viability.

Feed rate optimization

Scenario 2 was selected as the baseline for optimization iterations as it was identified as the most economically viable scenario. Figure 6(a) through to 6(e) indicate that reductions

Table 9. Production costs per annum.¹⁵

Cost category	Cost factor	Fixed/ variable cost	Annual cost (\$)
Direct production costs			850 129
Feedstock costs		V	139 807
Labor	0.15	F	194 721
Direct supervision	0.15	F	29 208
Utilities	0.15	V	194 721
Maintenance	0.06	F	183 078
Consumables	0.15	F	27 462
Laboratory fees	0.15	F	29 208
Patents and royalties	0.04	V	51 926
Fixed production costs			244 505
Local tax	0.015	F	45 769
Insurance	0.0125	F	38 141
Depreciation	0.053	F	160 595
Plant overheads	0.5	F	203 503
General costs			255 361
Administration costs	0.5	F	97 360
Distribution and marketing	0.07	V	122 889
Research and development	0.02	F	35 111
Contingency	0.025	F	38 837
Total production costs			1 592 336
Fixed cost			1 082 994
Variable cost			509 342

in fertilizer feed rate percentages tend to improve economic performance, largely due to the high cost of fertilizers in comparison with biomass, despite increases in total feed rate improving economic performance overall.

At loadings less than 20%, the IRR becomes positive for feed rates above 16 255 kg day⁻¹ while a 50% loading is not economically viable at feed rates less than 50 000 kg day⁻¹. Figure 6(d) and (e) also presents PP results, with Fig. 6(e) more clearly illustrating the feed rate's effect over the 20-year project lifespan.

Increasing the overall feed rate improved economic performance indicators but the interplay between biomass cost and fertilizer loading remained an important factor in determining costs. The contrast in fertilizer and biomass cost significantly impacted profit, with the consideration that fertilizers accounted for a considerable share of the feedstock cost. It was most evident at higher fertilizer loadings, where high input costs of fertilizers balanced against revenue increases, leading to negative and low IRR values.

Enriched biochar yield optimization

Biochar yield optimization is an important consideration in determining revenue potential and scalability. Higher biochar yield results in lower production of volatile pyrolysis fractions, which limits secondary revenue through the sale of syngas and pyrolysis oil. Maximizing biochar recovery enhances profitability through direct sales but it comes at the expense of potential co-product utilization, affecting overall plant economics.

Financially, increasing biochar yields improved economic indicators (Fig 7(a–e)). However, at 50% loading, a 60% biochar yield was still economically unfavorable, with

Table 10. Sales and costing summary.

Costing factor	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Units
Biochar sales	1 305 019	1 305 019	1 305 019	1 305 019	\$ year ⁻¹
Fertilizer sales	228 171	228 171	228 171	228 171	\$ year ⁻¹
Wood vinegar sales	0	0	358 206	219 811	\$ year ⁻¹
Electricity sales	411 642	223 370	0	0	\$ year ⁻¹
Phenolics sales	0	537 242	0	537 242	\$ year ⁻¹
Raw materials costs	9 423	9 423	9 423	9 423	\$ year ⁻¹

Table 11. Financial metrics for economic feasibility.

Financial indicator	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Units
NPV	-2 861 854	128 041	-4 260 691	109 384	\$
IRR	-7.3	0.3	-12.2	0.2	%
ROI	18.7	26.5	13.8	26.5	%
PP	24.9	12.7	48.4	12.7	Years

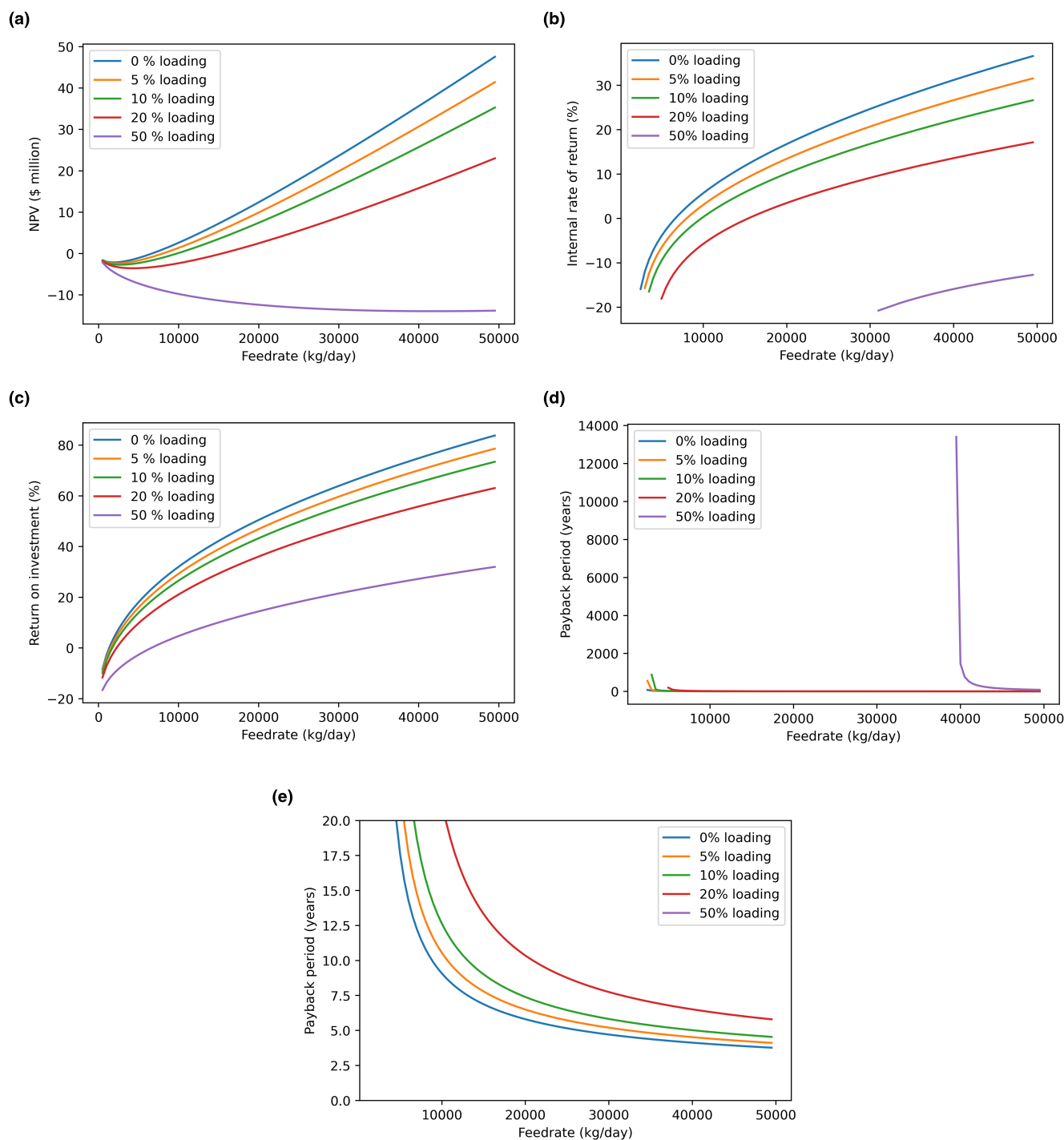


Figure 6. Financial indicators for different feed rates and fertilizer loadings. (a) NPV. (b) IRR. (c) ROI. (d) PP. (e) PP (20 year).

an IRR of -3.8% . The PP exceeded 400 years with 50% loading, illustrating that economic feasibility is heavily dependent on achieving an optimized tradeoff between char recovery and co-product utilization. In contrast, other fertilizer loadings (*i.e.*, 0%, 5%, 10%, and 20%) showed PPs of under 12 years.

Fertilizer ratio optimization

The optimization of N, P, and K ratios aimed to achieve a balanced ratio between each of the elemental fertilizing agents. Initial assessments showed that equal mass distribution of fertilizing agents resulted in K dominating the

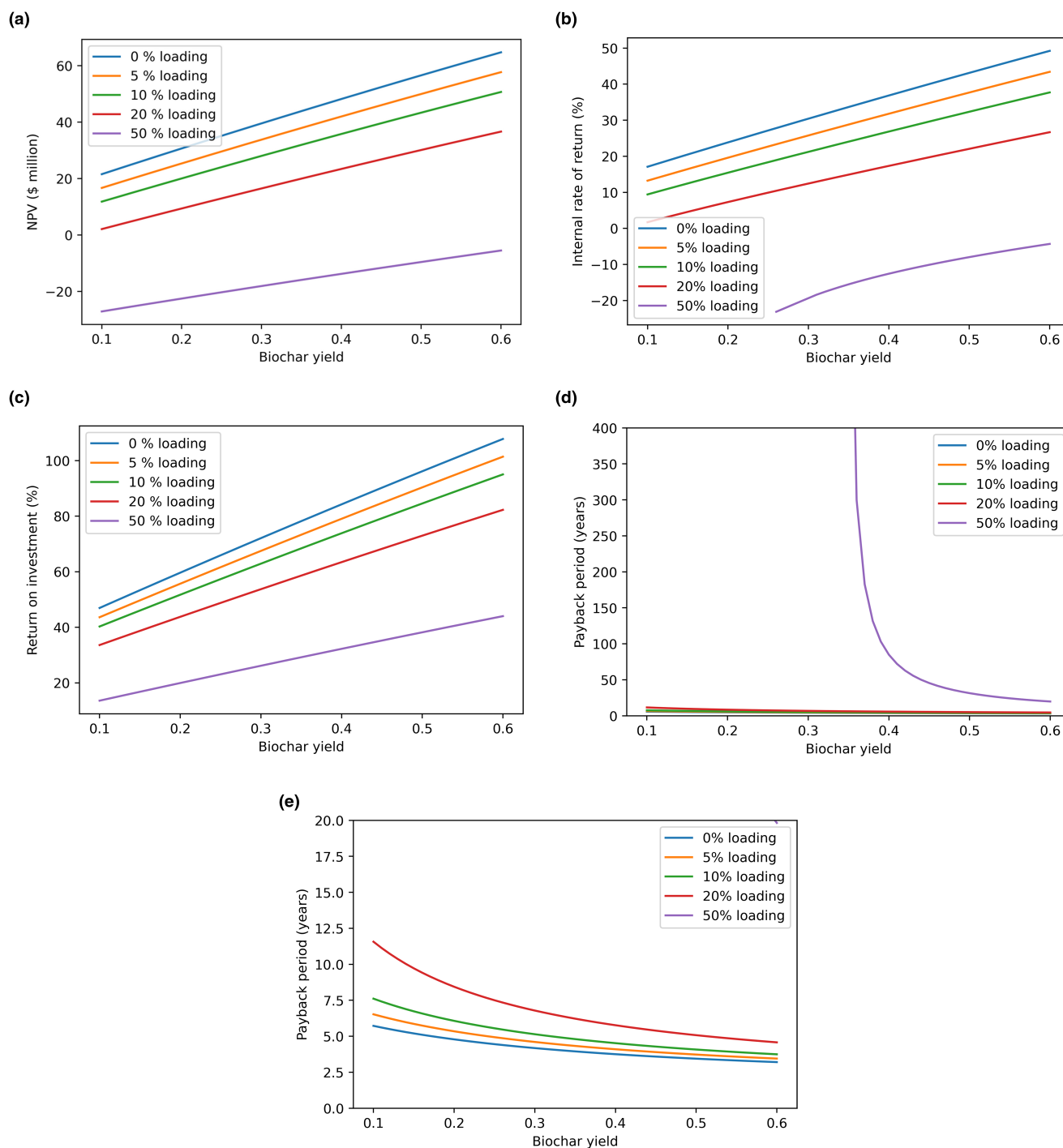


Figure 7. Financial indicators with a range of enriched biochar yields. (a) NPV. (b) IRR. (c) ROI. (d) PP. (e) PP (20 year).

mixture (Table 12) when 33% of each compound was added, yielding an NPK ratio of 0.15:0.13:1.00 (12%N, 10%P, and 78%K).

The exploration of different NPK ratios revealed that the optimal P mass fraction was achieved at $\omega_p = 0.20$. To achieve this maximum mass fraction, K_2CO_3 was limited to

$\omega_K = 0.05$ while the other two agents were iterated for in increments. The costs of urea and MOP (used to approximate costs associated with $Ca[NO_3]_2$ and K_2CO_3) were similar while DAP (representing K_3PO_4) was significantly more expensive. However, optimizing the fertilizer ratio based on cost had limited impact because the maximum P fraction

Table 12. NPK mass fractions of fertilizing agents.

Compound	Nitrogen (N)	Phosphorus (P)	Potassium (K)
K ₃ PO ₄	0.00	0.15	0.55
K ₂ CO ₃	0.00	0.00	0.57
Ca(NO ₃) ₂	0.17	0.00	0.00

was only 0.20. Thus, the final ratio was optimized for an even distribution of nutrients, resulting in an NPK ratio of 0.25:0.24:1.00 (17% N, 16% P, and 67% K) using a mix of 45% Ca(NO₃)₂, 50% K₃PO₄, and 5% K₂CO₃.

Selling price optimization and feasibility

A 75% fertilizer markup produced a selling price of \$1.55 per kg in the initial iteration, resulting in enriched biochar prices ranging from \$1.56 per kg (50% loading) to \$1.59 per kg (5% loading). The fertilizer price exceeded that of the biochar, therefore higher fertilizer loadings reduced profit margins and weakened financial performance, with viability observed only at loadings of 20% or less. Consequently, the biochar price was varied between \$0.01 and \$1.36 per kg to assess its potential as an industrial fertilizer enhancer, and the fertilizer markup was reduced to 0% to limit its impact on profitability.

Figure 8(a)–(e) illustrates that a 50% fertilizer loading was not financially viable, with no loadings achieving a PP of under 4 years. Project viability depends on multiple factors, including financial indicators, market positioning, and regulatory compliance.³⁴ As an IRR of between 14% and 18% is typical in the chemical industry, an IRR of 16% was used for fertilizer-enriched biochar, as it represents the midpoint of the industry-recommended range.³⁴ There are multiple ways to achieve the enriched biochar (EB) selling price, as it depends on both the biochar selling price and the fertilizer markup. For example, with a 50% fertilizer loading, a biochar price of \$1.58 per kg combined with a 197% fertilizer markup resulted in an enriched biochar price of \$2.13 per kg and an IRR of 16%. The associated ROI was 82.5% with a NPV of \$23.49 million (Table 13).

Nutrient requirements per hectare for various crops were adapted from previous data³⁵ and are presented in Table 14 to compare these quantities with enriched biochar and offer further insights into the additional cost for farmers. The focus was placed on crops like sugarcane and subtropical fruits/nuts, given their higher K and N needs. For this comparison, urea, DAP, and MOP were converted into equivalent N, P, and K costs per kilogram using the fertilizer costs of Table 2. Crops that require higher inputs of fertilizer agents per hectare (Table 14) include subtropical fruits/nuts (N:P:K = 180:12:199 kg ha⁻¹), sugarcane (N:P:K = 92:12:110 kg ha⁻¹), vegetables

(N:P:K = 170:35:100 kg ha⁻¹) and potatoes (N:P:K = 170:30:100 kg ha⁻¹). Costs associated with neat fertilizer use tend to be much cheaper in comparison with costs for enriched biochar applications (Table 15). Nevertheless, the costs associated with enriched biochar applications of those crops that demand the most fertilizer additions, namely sugarcane (\$25.86 ha⁻¹) and subtropical fruits/nuts (\$46.87 ha⁻¹), were found to decrease with higher fertilizer loadings, as much less enriched biochar was required to satisfy the required fertilizer loadings. For instance, approximately 19 kg of enriched biochar was needed to provide 1 kg of fertilizer at a 5% loading. Nineteen times the amount of enriched biochar must therefore be spread on a hectare of land to achieve fertilizer amounts that are similar to that achieved in the application of neat fertilizers. Conversely, only 1.93 kg of enriched biochar is required to produce 1 kg of fertilizer using a 50% fertilizer loading. Table 15 highlight that K is the most expensive component of fertilizers, being accentuated by its high mass fraction. This leads to significantly higher costs per hectare when using enriched biochar, with the price ranging from 32 to 127 times more than for traditional neat fertilizer use depending on the crop. This analysis raises an important question: do the long-term benefits of enriched biochar such as improved soil health justify its initial cost of application? The significant increase in expenses compared to traditional fertilizers makes enriched biochar economically unsustainable for most farmers at least in the short term, despite its potential long-term advantages for soil quality.

These findings highlight a fundamental challenge to the commercialization of biochar: nutrient-enriched biochar offers agronomic benefits but its high production costs relative to conventional fertilizers severely limit adoption, especially among resource-constrained farmers. As cost savings from reduced reliance on fertilizers might only be realized after a few years of growth cycles, economic feasibility remains uncertain in the short term. From a policy perspective, adoption could improve through government subsidies, incentives, or carbon credit mechanisms that offset initial investment costs. Innovations in commercialization of co-products – expanding the use of pyrolysis oil – can improve the economic standing of enriched biochar operations. Overall, the results indicate that optimization improved financial viability to some extent, but enriched biochar remains economically challenging.

Conclusions and recommendations

This article assesses the potential utilization of a fertilized-catalyzed pyrolysis for the synthesis of fertilizer-enriched biochar for use in the agricultural sector by way of a

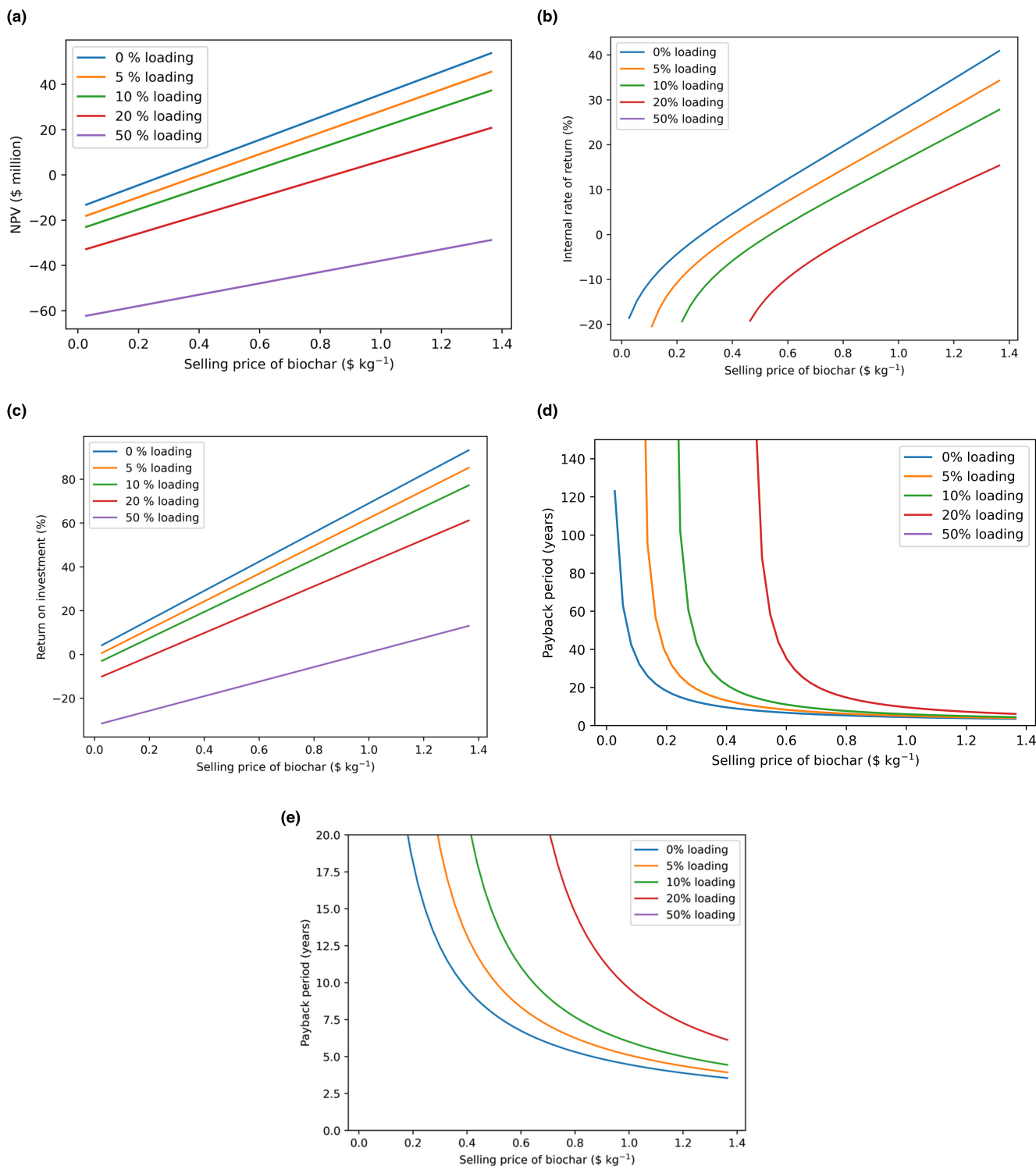


Figure 8. Financial indicators with a range of biochar selling prices. (a) NPV. (b) IRR. (c) ROI. (d) PP. (e) PP (20 year).

comprehensive techno-economic feasibility analysis. The economic potential of this process used four key financial indicators with a particular focus placed on the IRR and PP. Following optimizations of feed rate, biochar yield, and

fertilizer ratios, a target IRR of 16% and a PP of less than 10 years were achieved, which were further aligned with the plant's 20-year lifespan. A comparison of four scenarios that utilized co-products from the pyrolysis process in various

Table 13. Enriched biochar selling price with an internal rate of return (IRR) of 16%.

Loading (%)	Fertilizer mark-up (%)	EB selling price (\$ kg ⁻¹)	NPV (\$ mil)	ROI (%)
5	115	0.85	20.81	52.4
10	59	0.99	21.11	55.7
20	30	1.28	21.66	62.4
50	13	2.13	23.49	82.4

Table 14. Fertilizer application rates.

Crop	N (kg ha ⁻¹)	P (kg ha ⁻¹)	K (kg ha ⁻¹)
Maize	55	7	5
Wheat	30	9	3
Sunflower	15	5	2
Soybeans	7	5	7
Sugar cane	92	12	110
Lucerne	15	13	20
Other pastures	50	10	6
Tobacco	38	31	81
Cotton	36	5	2
Citrus	80	8	50
Subtropical fruits/nuts	180	12	199
Vines	50	8	20
Deciduous fruit	110	35	69
Vegetables	170	35	100
Potatoes	170	35	100

Table 15. Cost per hectare using neat fertilizer and enriched biochar.

Loading (%)	N (\$ ha ⁻¹)	P (\$ ha ⁻¹)	K (\$ ha ⁻¹)	Total cost (\$ ha ⁻¹)
Sugarcane with enriched biochar				
Neat fertilizer	6.98	1.07	17.81	25.86
5	1010	133	2146	3289
10	590	78	1253	1920
20	380	50	807	1237
50	255	34	543	832
Subtropical fruits/nuts with enriched biochar				
Neat fertilizer	13.66	1.07	32.14	46.87
5	1977	131	3881	5996
10	1154	77	2266	3500
20	743	49	1459	2254
50	500	33	981	1516

ways found that Scenario 2, which involved selling electricity back to the grid and distilling pyrolysis oil to extract a phenolic fraction, was the most economically feasible option.

Despite this, fertilizer-enriched biochar was still found to be economically unattractive due to its high cost compared to traditional fertilizers, particularly for crops with high K requirements. Enriched biochar offers long-term benefits for soil health and sustainability but its high up-front cost makes it financially unattractive for farmers. This analysis highlights the need to understand long-term sustainability regarding enriched biochar, taking into consideration the environmental 'costs' of conventional fertilizers such as their impact on climate change. Economic feasibility was evaluated primarily based on NPV, IRR, ROI, and PP, without any assumptions in terms of debt-equity distributions or any weighted average cost of capital. A target IRR of 16% was anticipated to represent an economically viable investment threshold but optimization results indicate that the project did not meet this criterion under current parameter assumptions.

Further research is recommended to investigate the relationship between the long-term benefits and physical properties of fertilizer-enriched biochar, as well as enriched biochar's potential as a slow-release fertilizer. For instance, despite the high upfront costs, the frequency of fertilizer-enriched biochar application may be considerably lower than neat fertilizer applications, thereby improving the long-term economic viability. A detailed life cycle analysis focusing on the sustainability and environmental impact of fertilized biochar is also necessary to assess its long-term environmental benefits and potential harm against its immediate economic challenges. Finally, policy interventions such as subsidies or carbon credits could help offset the immediate high costs and encourage wider adoption of biochar technologies in the sector.

In conclusion, although fertilized biochar is considered as an environmentally friendly method of managing fertilization of croplands, its current economic outlook is less favorable than conventional options when assessing the technoeconomic feasibility of the technology without considering its nonfinancial and indirect financial benefits.

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