

Research article

Techno-economic assessment of bioleaching for metallurgical by-products

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ABSTRACT

This study focused on the economic feasibility of two potential industrial-scale bioleaching technologies for metal recovery from specific metallurgical by-products, mainly basic oxygen steelmaking dust (BOS-D) and goethite. The investigation compared two bioleaching scaling technology configurations, including an aerated bioreactor and an aerated and stirred bioreactor across different scenarios. Results indicated that bioleaching using *Acidithiobacillus ferrooxidans* proved financially viable for copper extraction from goethite, particularly when 5% and 10% pulp densities were used in the aerated bioreactor, and when 10% pulp density was used in the aerated and stirred bioreactor. Notably, a net present value (NPV) of \$1,275,499k and an internal rate of return (IRR) of 65% for Cu recovery from goethite were achieved over 20-years after project started using the aerated and stirred bioreactor plant with a capital expenditure (CAPEX) of \$119,816,550 and an operational expenditure (OPEX) of \$5,896,580/year. It is expected that plant will start to make profit after one year of operation. Aerated and stirred bioreactor plant appeared more reliable alternative compared to the aerated bioreactor plant as the plant consists of 12 reactors which can allow better management and operation in small volume with multiple reactors. Despite the limitations, this techno-economic assessment emphasized the significance of selective metal recovery and plant design, and underscored the major expenses associated with the process.

1. Introduction

The high metal content found in metal-bearing wastes and by-products, such as metallurgical slag and dust, e-waste, and fly ash, is often similar or surpasses that of primary ore. This characteristic renders them invaluable as secondary resources within the circular economy (Kinnunen and Hedrich, 2023). Consequently, several studies are increasingly focusing on the feasibility of extracting metals from these secondary resources, driven by rising metal demands, declining concentrations in primary ores, and the imperative for improved environmental stewardship (Owusu-Fordjour and Yang, 2023; Tezyapar Kara et al., 2023a). While conventional methods such as pyrometallurgy and hydrometallurgy are predominantly used for metal extraction from primary ores, they require a significant amount of energy due to high temperature and pressure requirements, substantial capital investment, and the generation of harmful emissions (Arya and Kumar, 2020; Asghari et al., 2013). Moreover, these technologies are deemed inefficient due to metal losses during processing (Roy et al., 2021a, 2021b). In this context, bioleaching has emerged as an environmentally friendly and economically viable alternative for extracting metals from

secondary resources (Owusu-Fordjour and Yang, 2023; Al Sultan and Benli, 2023). Bioleaching, one of the biohydrometallurgical methods, relies on using naturally occurring microorganisms and/or their metabolites to extract metals from solid matrixes (Srichandan et al., 2019; Tezyapar Kara et al., 2023a). While commercial-scale bioleaching is available for metal extraction from sulfidic ores, tailings, and metallurgical side streams (Kinnunen and Hedrich, 2023; Kržanović et al., 2019; Petersen, 2023), there is currently no existing plant specifically designed for other secondary resources (Owusu-Fordjour and Yang, 2023; Thompson et al., 2018). This is partly due to the lack of techno-economic assessment (Vo et al., 2024).

While there is a scarcity in techno-economic assessment (TEA) of biomining for secondary resources, recent research showed that TEA is an effective tool for assessing the initial economic viability of a process or technology and identifying the main costs (Van Yken et al., 2023; Thompson et al., 2018). Specifically, Van Yken et al. (2023) assessed the economic viability of extracting and recovering metals from printed circuit boards (PCBs) using an integrated bio- and hydrometallurgical plant that can process 1000 tonnes of PCBs per year. The process included three operation units as follows: 1) generation of biogenic

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H₂SO₄ by sulphur-oxidising microorganisms, 2) generation biogenic ferric (Fe³⁺) by iron-oxidising microorganisms, and 3) indirect non-contact bioleaching of base metals from milled PCBs with the biogenic lixiviant. Results showed that increasing the PD to 5% from 1% with pH control significantly reduced the operating costs, resulting in an annual profit of 2749 Australian dollar (AUD)/t PCBs. Labour cost and annualised capital cost were found as largest contributors of the operating cost. In another study, Irrgang et al. (2021) projected a NPV > \$28M from bioleaching zinc sulphide to recover zinc, copper and indium using a thermophilic microbial consortium in continuously stirred tank reactors (CSTR) over 20 years. Similarly, Thompson et al. (2018) assessed the economic viability of extracting rare earth elements (REEs) from fluidized catalytic cracking (FCC) catalysts by using a heterotrophic bacterium, *Gluconobacter oxydans*, to produce organic acids from glucose. The TEA showed that the glucose was the single largest (44%) expense for the bioleaching process, suggesting that cheaper carbon and energy sources could significantly increase profitability. Further exploring cost-effective sources, Jin et al. (2019) demonstrated that using a corn stover would reduce total costs by 22% compared to potato wastewater, and potato wastewater would represent a 17% cost reduction compared to the use of glucose. In line with this, Alipanah et al. (2023) conducted a TEA for an industrial-scale bioleaching plant capable of processing 10,000 tonnes of black mass annually. They estimated that bioleaching process using a biolixiviant produced from corn stover by *Gluconobacter oxydans* can generate an average net potential value (NPV) of \$110M over 30 years. Black mass purchasing price and iron sulphate consumption as reducing agent were the two main expenses in their process. These findings highlight the importance of selecting economical substrates for biolixiviant production. In this study, the economic feasibility of two potential industrial scale bioleaching technologies, including an aerated and an aerated and stirred bioreactors were evaluated for metal recovery from metallurgical by-products, including basic oxygen steelmaking dust (BOS-D) and goethite. The assessment considered different operational conditions such as pulp density, energy source concentration (FeSO₄·7H₂O as a source of Fe²⁺), inoculum concentration, and pH and evaluated their effects on operational costs. Five scenarios were considered as follows: (i) extracting and recovering all nine elements (Y, Ce, Nd, Li, Co, Cu, Zn, Mn and Al) in elemental form by electrowinning, (ii) recovering only Zn in elemental form via electrowinning, (iii) recovering only the most abundant element, excluding Zn, in elemental form via electrowinning, (iv) recovering one of the critical metals, Li, and (v) recovering one of the REEs, Y. Zn recovery was specifically targeted as these metal-bearing by-products are potentially considered as a secondary iron resource due to their high iron content (40–60%); however, their high zinc content (10–100 g/kg) restricts their use in the blast furnace for the steelmaking industry (Xue et al., 2022). The reason is that when zinc charged into a blast furnace, it vaporizes at high temperatures (1600–1650 °C) due to its low boiling point (907 °C). Zinc condenses and accumulates on blast furnace walls that affect the solid and gas flows through the furnace. This can decrease the productivity and damage the furnace linings (Stewart and Barron, 2020; Xue et al., 2022). Zinc also shortens the furnace operating life by attacking refractories in the upper stack of the furnace (Binnemans et al., 2020). So, one of our focuses was evaluating the high Zn extraction conditions. This research provides insights into the potential value of extracted elements, emphasizes the importance of selective metal recovery and process design, and highlights the highest costs of the process.

2. Materials and methods

2.1. Characterisation of materials and metal values

A bulk mixture of BOS-D from a former iron and steelwork plant stockpiled in Teesside, UK, was received in a large, sealed drum and stored at ambient temperature. Additionally, goethite, a mineral residue

from zinc ore refining throughout a hydrometallurgical process, was obtained from the Nyrstar plant in Aubry, France and stored in a bucket at ambient temperature. Roughly 3 kg of samples from each by-product were used for analysis and experiments. Both samples were air-dried, ground, and sieved through a 2 mm mesh. The physico-chemical characteristics for BOS-D and goethite were analysed as described by Tezyapar Kara et al. (2022). The elemental composition of the autoclaved and non-autoclaved materials was determined using aqua regia digestion, with 1:3 ratio of nitric acid (HNO₃) and hydrochloric acid (HCl), followed by microwave digestion as described by Gutiérrez-Gutiérrez et al. (2015). Extracts were analysed with a PerkinElmer NexION® Inductively Coupled Plasma Mass spectrometer (ICP-MS) using uranium (U) as internal standard. Single ICP-MS standard solutions sourced from PerkinElmer for calibration were used with the analyte concentration of 10 µg/ml. For bioleaching study, autoclaved BOS-D, for 15 min at 121 °C, was used to ensure precise evaluation of the targeted microbial activity and metal leaching without interference from the native microorganisms (Faraji et al., 2018; Gomes et al., 2018). In this study, the techno-economic extraction assessment encompassed nine elements, including Yttrium (Y), Cerium (Ce), Neodymium (Nd), Lithium (Li), Cobalt (Co), Copper (Cu), Zinc (Zn), Manganese (Mn), and Aluminum (Al). These elements were selected based on their abundance, significance as critical metals, and inclusion as REEs. Unless stated otherwise, the currency referred to in this study is US dollar (\$).

2.2. Process description

This technoeconomic assessment evaluated two distinct industrial scale bioleaching technologies, including an aerated bioreactor based on the study of Isildar (2016) and a combined aerated and stirred bioreactor based on the study of Irrgang et al. (2021) (Table 1). The size of the aerated bioreactor is 5000 m³, with an effective volume of 4944 m³. The bioreactor is designed to introduce air from the bottom. This configuration serves multiple purposes: (i) aiding the oxidation of the leaching of metals, (ii) supplying the necessary oxygen and carbon dioxide for microbial activity, and (iii) facilitating leachate circulation by creating internal channels within the by-product in the reactor. In this study, it was assumed that the by-products are ground to a size smaller than 500 µm. Following the completion of bioleaching, the targeted metals are recovered from the leachate in their elemental form through electrowinning. To ensure comparability with the study conducted by Isildar (2016), the initial size of the combined aerated and stirred bioreactor outlined by Irrgang et al. (2021) was doubled (Table 1). Therefore, 12 aerated and stirred bioreactor were selected with a 450 m³ volume and

Table 1
Details of the equipment requirements and costs for each bioreactor.

Bioreactor type	Process unit	Unit number	Costs (\$/unit)	Total costs (\$)
Aerated bioreactor (Isildar, 2016)	Grinding	5	27,213	136,065
	Bioreactor (5000 m ³)	1	9383	9383
	Electrowinning cells	9	34,016	306,147
	TPEC			451,596
Aerated and stirred bioreactor (Irrgang et al., 2021)	Grinding	2	282,000	564,000
	Bioreactor (450 m ³)	12	1,695,000	20,340,000
	Measurement/Sensor technology	12	19,217	230,600
	Cooling	16	141,250	2,260,000
	Aeration	26	6446	167,600
	Extraction	1	3,738,300	3,738,300
	Electrowinning (copper)	1	180,360	180,360
	Electrowinning (other elements)	1	8,126,220	8,126,220
	TPEC			35,607,080

445 m³ effective volume of each reactor. The aerated and stirred bioreactor is equipped with state of art technologies such as measurement/sensor technology, cooling, aeration, extraction and electro-winning equipment. The schematic process designs for the aerated bioreactor plant and the aerated and stirred bioreactor plant are shown in Fig. 1.

The equipment data for the aerated and stirred bioreactor was more current, dating from 2021, in contrast to the aerated bioreactor which dated from 2016. Hence, the cost data for the aerated bioreactor were extrapolated for 2021 using the Chemical Engineering Plant Cost Index (CEPCI) as described in Equation (1) (Bacatelo et al., 2023; Peters and Timmerhaus, 1991; Isildar, 2016):

$$C = C_0 \times \left(\frac{CEPCI}{CEPCI_0} \right) \quad (1)$$

Where C_0 is cost in 2016, C is cost in 2021, $CEPCI_0$ is CEPCI in 2016 (541.7) and $CEPCI$ is CEPCI in 2021 (677.7). Since the recent CEPCI index is available for 2021, cost data was extrapolated for this year.

Parameters considered for both technologies are summarised in Table 2 and adapted from Irrgang et al. (2021) and Dewulf (2022). An overall plant efficiency of 95% was assumed, plant lifespan of 20 years,

annual working hour and annual working days were chosen according to Irrgang et al. (2021) and Isildar (2016). The leaching duration for the aerated bioreactor was 11 days, whereas for the combined aerated and stirred bioreactor, it was extended to 16 days, as determined from the laboratory experiments as described in Section 2.3. The number of leaching cycles per year was then calculated based on leaching duration and plant capacity (Dewulf, 2022). By-product processing quantities were derived by considering leaching cycles and pulp density (PD) (Dewulf, 2022). In Section 2.2, bioleaching batch experiments, the PD were 1, 5 and 10% (w/v). The number of bioleaching cycles per year (n/y) was obtained by dividing the annual working day by the duration of one bioleaching cycle. Any resulting fractions were rounded down, and the obtained cycle number was reduced by one to take into account potential failures. The capacity of material processed in one bioleaching cycle was calculated using bioreactor volume and PD information. The plant capacity (t/y) was subsequently determined by multiplying the material amount that can be processed in one bioleaching cycle and the number of bioleaching cycles per year (n/y). Based on these assumptions, the processing capacities of the aerated bioreactor were estimated at 1434 t/y when 1% PD was used, 7169 t/y with 5% PD, and 14,338 t/y with 10% PD. Similarly, the processing capacities of the aerated and stirred bioreactor were estimated at 1015 t/y with 1% PD, 5073 t/y with

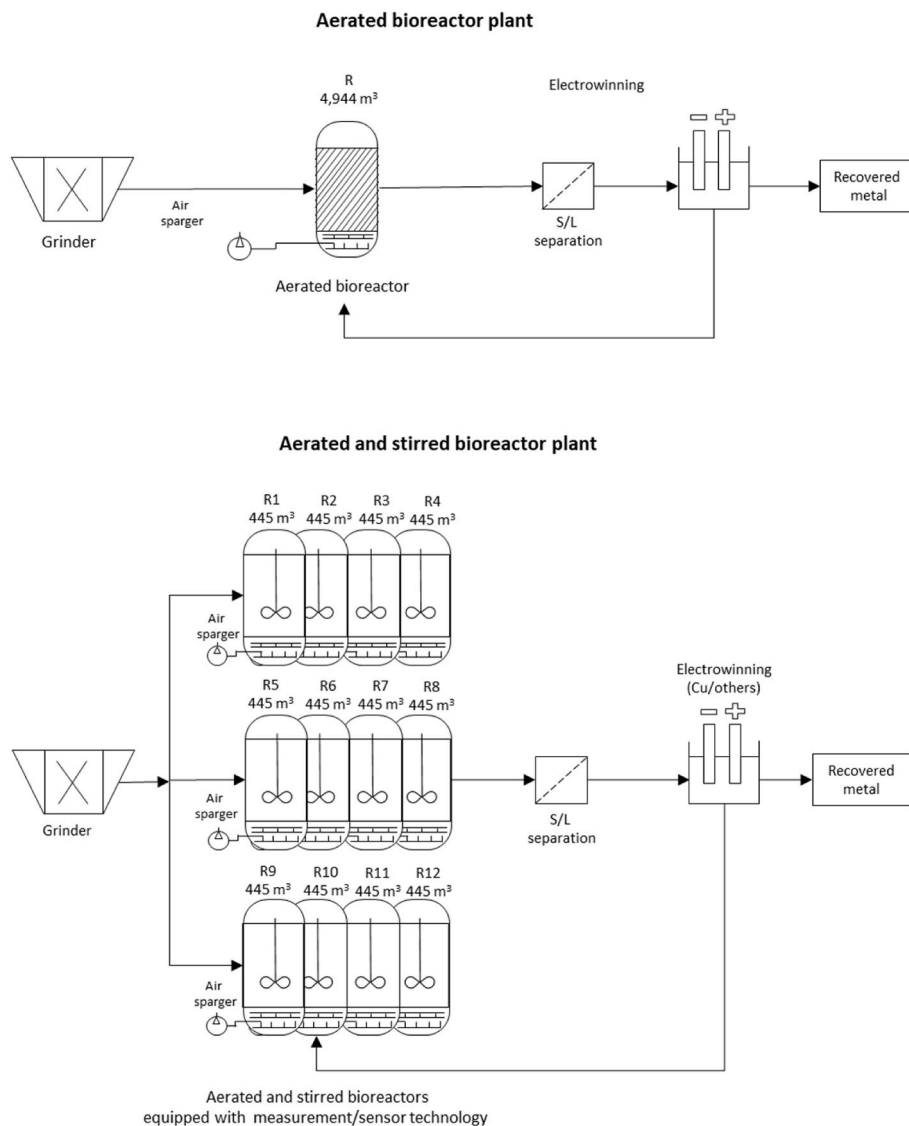


Fig. 1. Schematic process design for both the aerated and the aerated and stirred bioreactor plants for metal recovery from industrial metal-bearing by-products (Isildar, 2016; Irrgang et al., 2021).

Table 2

Parameters and metrics used for the industrial scale bioreactors.

Bioleaching reactor types		Aerated			Aerated and stirred		
Description	Units	Value					
Annual working hour	h/y	8000					
Annual working day	d	334					
Overall plant efficiency	%	95					
Plant life	y	20					
Bioleaching duration	d	11			16		
Bioleaching cycle	n/y	29			19		
Pulp density	% (w/v)	1%	5%	10%	1%	5%	10%
Plant capacity	t/y	1434	7169	14,338	1015	5073	10,146
Total processed material	t	28,680	143,380	286,760	20,300	101,460	202,920

5% PD, and 10,146 t/y with 10% PD.

2.3. Experimental setup and revenues calculations

A series of bioleaching batch experiments were performed for 16 days under different solid concentration, energy source concentration, inoculum concentration which are detailed in Table S4 (Tezyapar Kara et al., 2023b). It should be noted that the focus of the study was optimisation of the bioleaching and evaluation the influence of varying operational parameters; hence, abiotic and acid controls have only been carried out for 1% PD at pH 1.75. For accurate interpretation, any profitable bioleaching condition should be compared with the appropriate abiotic and acid controls to understand the effect of the *Acidithiobacillus ferrooxidans*. An adapted *A. ferrooxidans* culture and optimised growth medium were used for bioleaching experiments as detailed in Tezyapar Kara et al. (2023b). The optimised growth media consist of modified basal salt medium (MBSM) and a ferrous iron solution. MBSM was prepared by adding 2 g of $(\text{NH}_4)_2\text{SO}_4$, 0.25 g of K_2HPO_4 , 0.25 g of $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, 0.10 g of KCl and 0.01 g of $\text{Ca}(\text{NO}_3)_2$ –700 ml of deionised water (Chen et al., 2015). The ferrous iron solution was prepared by adding varying amounts of $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ as a source of ferrous iron, based on the optimisation level, to 300 ml deionised water as detailed in Table S4 and Tezyapar Kara et al. (2023b). Briefly, the batch experiments were performed using 250 mL Erlenmeyer flasks under 100 ml working volume, incubated at 30 °C on an orbital shaker at 150 rpm. It was assumed that the orbital shaker could effectively replicate an industrial aerated and stirred bioreactor (Heyman et al., 2019; Irrgang et al., 2021). Additionally, a column experiment was performed for 11 days, focusing solely on BOS-D under 1000 ml working volume with the condition given in Table S4 derived from batch optimisation experiments where leachate was circulated at 40 ml/min. BOS-D was selected as reference by-product to be investigated on column scale instead of processing both materials due to time and resource constraints. The column was run under submerged conditions, with air supply from the bottom of the columns, aiming to simulate an industrial aerated bioreactor setup (Isildar, 2016). Extracts were analysed with a PerkinElmer's NexION® Inductively Coupled Plasma Mass spectrometer (ICP-MS) using uranium (U) as internal standard as described. Single ICP-MS standard solution sourced from PerkinElmer for the metals with the analyte concentration of 10 µg/ml were used for calibration.

For the plant revenue calculations, the extraction yields (%) from batch experiments (Table S4) were used to calculate the revenue from aerated and stirred bioreactor assuming that the agitation conditions mimicked the stirred environment present in the aerated and stirred bioreactor (Pourhossein and Mousavi, 2019). On the other hand, the column experiment data (Table S4) was used to derive the extraction yield for the aerated bioreactor plant where for each element the extraction data was proportionally adjusted to compute the revenue. The total cost and revenue were determined based on five distinct scenarios: (1) Extraction and recovery of all nine elements (Y, Ce, Nd, Li, Co, Cu, Zn, Mn, and Al) in elemental form through electrowinning, (2) Recovery of zinc (Zn) only in elemental form via electrowinning and (3)

Recovery of the most abundant element, excluding zinc, in elemental form through electrowinning. For BOS-D, the most prevalent element was Mn, while for goethite, it was Cu, excluding zinc. (4) Extraction and recovery of one critical element, Li, and (5) Recovery of one REE, Y. The specific focus on zinc is due its significance, as its presence >1% content restricts the reusability the by-products as secondary iron resources. So, the extraction resulting Zn content <1% in the residue may potentially allow this metallurgical by-product to be considered as secondary resource (Xue et al., 2022). For these conditions additional revenue was added where the by-product was resold as secondary iron resource based on their iron content. It was assumed that 16% of iron from BOS-D and 18% of iron from goethite was loss during the leaching process according to acid control experiment. One tonne of 64% grade iron ore was \$155 (Trading Economics, 2023).

2.4. Techno-economic assessment

Details of on the total cost breakdown of the bioleaching process including the capital expenditure (CAPEX) and the operational expenditure (OPEX) are provided in Table 3. CAPEX includes equipment purchase and installation costs, piping costs, electrical, buildings, yard

Table 3

Overview of the CAPEX and OPEX for each bioreactor type.

CAPEX		
Direct cost	Typical range %	Assumed % of total
Purchased equipment	15–40	25
Purchased equipment installation	6–14	9
Instruments and controls (installed)	2–8	7
Piping (installed)	3–20	8
Electrical (installed)	2–10	5
Buildings (including services)	3–18	5
Yard improvement	2–5	2
Services facilities (installed)	8–20	15
Land	1–2	1
Indirect cost		
Engineering and supervision	4–21	10
Construction expense	4–16	12
Contractor's fee	2–6	2
Contingency	5–15	8
OPEX		
Utilities cost		
Water	2.47 \$/m ³	
Electricity	0.36 \$/kWh	
Grinding ^{a,b}	38 kW h/tonne ore ^a ; 60 kW h/tonne ore ^b	
Electrowinning ^{a,b}	1240 kW h/tonne metal ^a ; 714 kW h/tonne Cu ^b ; 3338 kW h/tonne metal ^b	
Aeration ^a	20 kW h/tonne metal	
Bioreactor ^b	2525 kW h/tonne metal	
Extraction ^b	60 kW h/tonne metal	
Maintenance and wear	5% of investment sum per year	
Personnel costs	50 positions, including labour, laboratory, administration.	
Reagent Cost	as per details in Table S3 in supplementary materials	

^a Input used for aerated bioreactor.

^b Input used for aerated and stirred bioreactor.

improvement, service facilities and land cost. Cost ranges and assumed values for each of these expense items are derived from Peters and Timmerhaus (1991). OPEX includes utilities cost such as water and electricity, maintenance and wear, personnel cost, and reagent cost (Irrgang et al., 2021; Thompson et al., 2018). As different equipment was used for the aerated bioreactor and the aerated and stirred bioreactor, specific energy requirements were considered. For instance, the energy requirement for the electrowinning equipment in the aerated bioreactor plant is 1240 kW h per tonne of metal extracted, whereas for the aerated and stirred bioreactor plant, it increases to 3338 kW h per tonne of metal extracted. The assumed costs were set at \$2.47 for 1 m³ of water and \$0.36 for 1 kW h of electricity. Because for this study the number of units of the aerated and stirred bioreactor plant was twice of the study of Irrgang et al. (2021), personnel costs were doubled accordingly. Considering the similar capacities of both plants, the personnel costs for the aerated bioreactor plant were assumed to be equivalent. Reagent costs were computed based on the laboratory experiment conditions, and the chemical commodity prices as detailed in Table S3.

The financial analysis was conducted using GoldSim version 14.0 (GoldSim Technology Group, 2021) to forecast cash flow, net present value (NPV), and internal rate of return (IRR) for the three scenarios. To ensure a more comprehensive and realistic feasibility analysis, the model incorporated discount rates and inflation rates (Fig. 2). Specifically, the model incorporated a discount rate of 10% and an inflation rate of 3.5%, aligning with established practices (Irrgang et al., 2021; GoldSim Technology Group, 2021). Furthermore, the model elements integrated development costs of \$10,000 per year for the initial two years (model default). Data for initial capital costs (TFCI), operating costs, and revenues were sourced from Tables 1–3 and S3.

3. Results and discussion

The elemental compositions of the autoclaved BOS-D and goethite are given in Table 4. BOS-D contains 1.30 g Y, 3.84 g Ce, 1.81 g Nd, 4.47 g Li, 10.16 g Co, 126.50 g Cu, 18,300 g Zn, 2660 g Al, 5870 g Mn and 390,500 g Fe per tonne while goethite contains 2.30 g Y, 5.60 g Ce, 2.40 g Nd, 3.20 g Li, 9.00 g Co, 203,667 g Cu, 61,615 g Zn, 11,164 g Al, 2457 g Mn and 162,333 g Fe per tonne. The elemental composition of non-autoclaved materials and the physico-chemical characteristics of BOS-D and goethite have also been given in supplementary materials (Tables S1 and S2). Table 4 indicates the estimated potential values of elements for per tonne processed metallurgical by-product under 100%

extraction efficiency. According to this, there is a potential value of \$133 per BOS-D processed and a value of \$1506 per goethite processed. The substantial difference between the values of BOS-D and goethite are due to the higher initial Copper (Cu) content found in goethite (203,667 g/t) compared to BOS-D (126.50 g/t). Additionally, these values may vary based on fluctuations in market prices and shifts in demand.

Based on varying operational conditions different extraction yields were obtain as shown in Table S4. The leaching kinetics decreased in the column setup (operational condition 1 | 1 | 1 | 1.75) compared to the batch (operational condition 1 | 1 | 1 | 1.50), resulting in decreased dissolution rates (Table S4). This occurrence could be due to less effective interactions between microorganisms, leaching agents, and materials in larger volumes, along with heat dissipation in the column arrangement, in contrast to the batch system.

3.1. Potential revenues and profits of the different bioreactors

Fig. S1 shows the potential revenues resulting from the different operational conditions and different scenarios based on aerated bioreactor plant capacity and experimental results. Processing BOS-D processing with the aerated bioreactor can generate a potential revenue ranging from \$126,284 and \$6,308,847. A significant portion of this value originated from zinc recovery, given its predominance in BOS-D. Meanwhile, the potential revenue from the various elements recovered from the goethite ranged between \$974,816 and \$228,932,495. Most of these revenues were attributable to Cu recovery, the most abundant element in goethite. However, assessing potential revenues alone is insufficient to gauge profitability, necessitating a comprehensive techno-economic assessment involving CAPEX and OPEX. According to this, detailed cost analysis was performed, and the estimated total profits of each scenario are given in Table 5. Notably, no profit was projected from BOS-D processing using the aerated bioreactor. In contrast, profits between \$16,029,208 to \$142,538,726 from goethite were estimated when 5% and 10% PD was used, respectively. As an illustration, a detailed breakdown of the total costs for recovering all nine elements and Cu from goethite using the aerated bioreactor is provided in Tables 6 and S5. Maintaining a constant plant capacity for each condition resulted in similar expenses for total fixed capital investment (TFCI), water, maintenance, and personnel costs. However, discrepancies were observed in electricity and reagent costs due to varying extraction yields, energy source concentration, and sulfuric acid consumption between the operational conditions. For instance, to recover all elements from goethite, the condition of 10 | 2 | 10 | 1.75 incurred an estimated cost of \$27,919,319 in electricity and reagent costs, while the condition of 10 | 3 | 1 | 2.00 incurred a cost of \$29,749,939 (Table 6). Although the latter condition had higher costs, the estimated profit of \$8.5M was greater compared to the more economical option. Energy source costs are as the highest expense among reagents (Table 6).

Similar trends were observed for the scenario where Cu is only recovered, where the condition of 10 | 3 | 1 | 2.00 incurred higher costs but yielded a higher estimated profit of \$9.7M compared to the condition of 10 | 2 | 10 | 1.75 (Table S5). Overall, the operational condition of 10 | 3 | 1 | 2.00 presented the highest potential profit for both scenarios. While the recovery of Cu only appeared more profitable due to lower processing costs for other elements, recovering all elements remained profitable, primarily owing to the value of copper. Personnel costs, followed by electricity and reagent costs, constituted the major expenses for the aerated bioreactor plant.

Using the aerated and stirred bioreactor, the potential revenues from extracting various elements from BOS-D and from goethite were estimated at \$274,625,691 (Fig. S2). Despite considering additional revenue from reselling BOS-D as a secondary resource, the configuration with the aerated stirred bioreactor did not yield profitability when CAPEX and OPEX were taken into account (Table S6). Conversely, projected profits ranging from \$3,038,728 to \$12,977,072 were

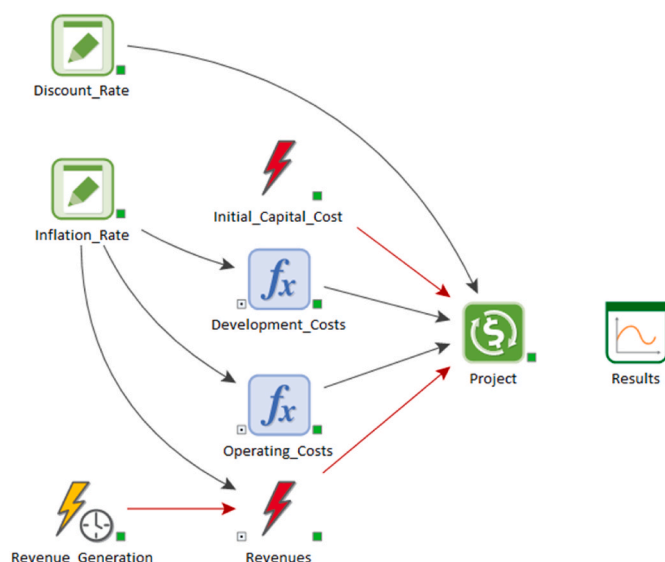


Fig. 2. Overview of the financial module elements.

Table 4
Estimated potential values of elements for per tonne processed metallurgical by-product, assuming 100% extraction efficiency.

Elements	Commodity price ^a (\$/t)			BOS-D				Goethite			
				Concentration (g/t)	Value of resource (\$/t)			Concentration (g/t)	Value of resource (\$/t)		
	Min	Max	Average		Min	Max	Average		Min	Max	Average
REE											
Y ^{b, e, f, h}	26,850	60,000	38,338	1.30	0.03	0.08	0.05	2.30	0.06	0.14	0.09
Ce ^{b, e, f, h}	5000	11,000	7093	3.84	0.02	0.04	0.03	5.60	0.03	0.06	0.04
Nd ^{b, d, e, f, h}	46,030	142,600	81,126	1.81	0.08	0.26	0.15	2.40	0.11	0.34	0.19
Total REE				6.95	0.14	0.38	0.22	10.30	0.20	0.54	0.32
Critical metals											
Li ^{b, f, g, h}	63,370	115,700	88,208	4.47	0.28	0.52	0.39	3.20	0.20	0.37	0.28
Co ^{b, f, g, h}	32,800	59,500	42,738	10.16	0.33	0.60	0.43	9.00	0.30	0.54	0.38
Cu ^{b, c, f, g, h}	4530	8490	6386	126.50	0.57	1.07	0.81	203,667	922.61	1729.13	1300.62
Total critical metals				141.13	1.19	2.20	1.64	203,679	923	1730	1301
Heavy metal and others											
Zn ^{c, f, g, h}	2170	2830	2466	18,300	39.71	51.79	45.12	61,615	133.70	174.37	151.92
Al ^{b, f, g, h}	1470	2032	1853	2660	3.91	5.41	4.93	11,164	16.41	22.69	20.69
Mn ^{f, h}	1580	2060	1820	5870	9.27	12.09	10.68	1457	2.30	3.00	2.65
Fe ^{f, g, h}	60	400	180	390,500	23.43	156.20	70.29	162,333	9.74	64.93	29.22
Total heavy metal and others		417,330	76	225	131	236,569	162	265	204		
Total elements				417,478	78	228	133	440,259	1085	1996	1506

^a Commodity prices of elements form various resources. Average value of each element was determined based on a range of reference demoted by number.
^b Gutiérrez-Gutiérrez et al. (2015).
^c KME (2023).
^d Strategic metals invest (2023).
^e Institute of Rare Earths and Metals (2019).
^f Compound Interest (2019).
^g Alan's Factory Outlet (2021).
^h Leon Becker (2018).

Table 5
Projected total profit of the aerated bioreactor considering varied operational conditions and extracted metals over 20 years (Conditions names represent the values of “solid concentration | energy source concentration | inoculum concentration | pH”).

	PD	Condition	9 elements	Zn	Mn	Li	Y
BOS-D	1%	1 1 1 1.50	-59,989,204	-58,888,484	-59,186,449	-59,273,499	-59,276,622
		1 2 5 1.75	-60,856,858	-59,740,545	-60,001,936	-60,088,891	-60,090,449
		1 3 10 2.00	-61,921,111	-60,807,972	-61,049,869	-61,143,565	-61,145,661
	5%	5 1 5 2.00	-60,564,674	-59,972,624	-61,487,729	-61,904,147	-61,913,820
		5 2 10 1.50	-65,204,168	-64,588,377	-65,850,243	-66,238,544	-66,242,082
		5 3 1 1.75	-64,443,612	-63,808,178	-65,046,588	-65,425,817	-65,430,000
	10%	10 1 10 1.75	-66,601,061	-66,548,469	-69,025,288	-69,782,887	-69,794,380
		10 2 1 2.00	-65,127,470	-65,157,869	-67,788,633	-68,645,199	-68,659,179
		10 3 5 1.50	-71,904,057	-71,775,704	-74,128,637	-74,823,124	-74,829,731
	PD	Condition	9 elements	Zn	Cu	Li	Y
Goethite	1%	1 2 1 1.50	-41,833,988	-59,040,455	-41,443,982	-59,790,133	-59,790,401
		1 3 5 1.75	-45,371,186	-59,734,117	-45,154,036	-60,655,428	-60,655,878
		1 4 10 2.00	-47,217,192	-60,936,755	-46,989,763	-61,857,973	-61,858,515
	5%	5 2 5 2.00	23,389,482	-57,366,114	20,625,140	-61,007,312	-61,008,495
		5 3 10 1.50	12,926,739	-60,589,309	10,219,122	-64,124,082	-64,124,491
		5 4 1 1.75	19,140,337	-61,096,553	16,111,079	-64,952,446	-64,953,703
	10%	10 2 10 1.75	125,017,937	-57,483,507	118,436,508	-64,552,747	-64,553,574
		10 3 1 2.00	133,590,932	-59,043,273	127,420,395	-65,683,431	-65,683,951
		10 4 5 1.50	124,384,020	-62,926,100	118,379,061	-69,353,101	-69,353,123

observed for goethite processing at 10% PD in bioleaching (Table S6), excluding the resale of goethite as a secondary resource. A detailed breakdown of the total costs for recovering Cu from goethite in the aerated and stirred bioreactor is provided in Table S7. Similar to aerated bioreactor plant, where the plant capacity was constant for each condition, several expense items, including total fixed capital investment

(TFCI), water, maintenance and wear, and personnel costs, remained consistent across all conditions. Nonetheless, discrepancies were still observed for the electricity and reagent costs due to different extraction yields, energy source concentration, and sulfuric acid consumption among operational conditions. As previously mentioned, despite higher expenses in one operational condition, the estimated profit could be

Table 6

Cost analysis for recovering all nine elements from goethite using aerated bioreactor over 20 years (Conditions names represent the values of “solid concentration | energy source concentration | inoculum concentration | pH”).

Pulp density	1%			5%			10%		
Condition	1 2 1 1.50	1 3 5 1.75	1 4 10 2.00	5 2 5 2.00	5 3 10 1.50	5 4 1 1.75	10 2 10 1.75	10 3 1 2.00	10 4 5 1.50
CAPEX									
Direct cost	1,390,915	1,390,915	1,390,915	1,390,915	1,390,915	1,390,915	1,390,915	1,390,915	1,390,915
Indirect cost	578,042	578,042	578,042	578,042	578,042	578,042	578,042	578,042	578,042
Total fixed capital investment	1,968,957	1,968,957	1,968,957	1,968,957	1,968,957	1,968,957	1,968,957	1,968,957	1,968,957
OPEX									
Utilities cost									
Water	7,077,594	7,077,594	7,077,594	7,077,594	7,077,594	7,077,594	7,077,594	7,077,594	7,077,594
Electricity									
Grinding	388,173	388,173	388,173	1,940,866	1,940,866	1,940,866	3,881,732	3,881,732	3,881,732
Electrowinning	1,647,794	1,463,775	1,410,607	7,371,266	6,790,370	7,391,629	16,250,068	16,950,311	16,495,691
Aeration	204,302	204,302	204,302	1,021,508	1,021,508	1,021,508	2,043,017	2,043,017	2,043,017
Total electricity	2,240,269	2,056,250	2,003,082	10,333,640	9,752,744	10,354,004	22,174,816	22,875,060	22,420,440
Maintenance and wear	98,448	98,448	98,448	98,448	98,448	98,448	98,448	98,448	98,448
Personnel costs	45,000,000	45,000,000	45,000,000	45,000,000	45,000,000	45,000,000	45,000,000	45,000,000	45,000,000
Reagent Cost	6,300,228	7,165,646	8,368,284	5,154,367	8,270,214	9,099,501	5,744,503	6,874,879	10,543,011
Total cost	62,685,496	63,366,895	64,516,365	69,633,006	72,167,958	73,598,504	82,064,318	83,894,938	87,108,450
Total revenue	20,851,508	17,995,708	17,299,172	93,022,488	85,094,697	92,738,841	207,082,255	217,485,870	211,492,470
Estimated profit	-41,833,988	-45,371,186	-47,217,192	23,389,482	12,926,739	19,140,337	125,017,937	133,590,932	124,384,020

greater owing to the higher revenue obtained. For instance, estimated electricity and reagent costs totalled \$58,739,395 for the condition 10 | 2 | 10 | 1.75 (10% PD, 2% energy source concentration, 1% inoculum concentration at pH 1.75), while for the condition 10 | 3 | 1 | 2.00 (10% PD, 3% energy source concentration, 1% inoculum concentration at pH 2.00), costs reached \$61,932,323. Although the latter condition incurred higher costs, the estimated profit of nearly \$10M was higher compared to the more economical option. Ultimately, condition 10 | 3 | 1 | 2.00 yielded the highest potential profit, amounting to \$12,977,072, for Cu recovery using the aerated and stirred bioreactor. For the aerated and stirred bioreactor plant, the highest expense was the electricity costs and personnel expenses.

3.2. Comparative financial analysis of recovery of elements from BOS-D and goethite

The emphasis for the financial analysis was focused on the recovery of the most abundant elements, including one critical element and one rare earth element present in the two metallurgical by-products under the following conditions: 10% PD, 2% energy source concentration, 1% inoculum concentration, pH 2 for BOS-D (Fig. 3) and 10% PD, 3% energy source concentration, 1% inoculum concentration, pH 2 for goethite (Fig. 4). It is evident that the cash flow and the NPV projections for Zn recovery from BOS-D using the aerated bioreactor show a consistent decline in profits over the 20-year period, showing a cumulative loss exceeding \$25,000,000 (Fig. 3a). Likewise, no profitability was observed within the 19 years after the project started for the aerated and stirred bioreactor plant. However, there is a potential for the plant to become profitable beyond this initial phase (Fig. 3b). Similarly, recovering Li and Y from BOS-D was not profitable using both of the aerated and the aerated and stirred bioreactor plants. Using the aerated bioreactor plant resulted in cumulative losses around 90,000 k\$ each for Li and Y. Although the yearly revenues were different for Li (\$994/year, Table S8) and Y (\$293/year, Table S10), they represented a small proportion compared to the OPEX (\$3,394,131/year for Li and \$3,394,129/year for Y) and TFCI, which is same for recovering Li and Y (\$782,466). Thus, individual recovery of Li and Y individually from BOS-D using the aerated bioreactor plant resulted in comparable cumulative losses of \$91,089k for Li (Fig. 3c) and \$91,314k for Y (Fig. 3e). A similar outcome was observed with the aerated/stirred bioreactor, generating revenues of \$34,980 from Li recovery and \$6629 from Y recovery over a 20-year period. Additionally, considering the 55% zinc bioleaching efficiency for

BOS-D (Table S4), it was assumed to be resalable as a secondary resource, yielding an additional revenue of \$11,364,027 over 20 years, assuming an initial zinc concentration of 1.8% (Table 4). Consequently, total revenue estimates for Li and Y recovery from BOS-D were \$11,399,007 and \$11,370,657, respectively (Table S11). Despite factoring in the additional revenue from BOS-D resale, the high OPEX (\$3,511,299 for Li and \$3,511,285 for Y) and TFCI (\$154,460,499) resulted in cumulative losses of \$65,331 for both Li and Y recovery from BOS-D (Fig. 3f and d).

In contrast to Zn recovery from BOS-D, the recovery of Cu from goethite is much more profitable (Fig. 4a and b). After 20 years of operation, the NPV for the aerated and stirred bioreactor plant reached 1,275,499 k\$ with an IRR of 65% (Fig. 4b). Meanwhile, the NPV and IRR for the aerated bioreactor plant were 1,166,997 k\$ and 745%, respectively (Fig. 4a). Despite the close NPV values, the aerated bioreactor plant exhibited an IRR over 10 times higher than the aerated and stirred bioreactor plant due to its lower initial capital and operational costs. It also suggests that it generates significantly greater returns relative to its initial investment compared to the aerated and stirred bioreactor. This higher IRR implies that, despite both scenarios being profitable, the aerated bioreactor has a more efficient utilisation of investment capital and generates higher returns per unit of invested capital than the aerated and stirred bioreactor over the given time frame. Yet, given the disparity in the equipment data, with the aerated bioreactor data sourced from a study published in 2016 and the aerated and stirred bioreactor data being sourced from a study published in 2021, caution is needed in extrapolating these results. Ultimately, the aerated and stirred bioreactor plant appears to be a more pragmatic alternative when compared to the aerated bioreactor plant as it potentially provides better management with multiple reactors with small volumes. The recovery of Li from goethite using the aerated bioreactor incurred a cumulative loss of \$87,201k with an annual revenue of \$773/year (Fig. 4c–Table S12). In contrast, using the aerated and stirred bioreactor configuration resulted in higher cumulative loss, reaching \$299,733k, with an annual revenue of \$1360/year (Fig. 4d–Table S13). Similarly, Y recovery using the aerated bioreactor plant resulted in a cumulative loss of \$87,208k, with an annual revenue of \$752/year (Fig. 4e–Table S14), whereas using the aerated and stirred bioreactor led to a higher loss of \$299,897k, with an annual revenue of \$850/year (Fig. 4f–Table S15). Although the revenues are different for Li and Y, the recovery scenarios from goethite using the same bioleaching plant configurations resulted in similar cumulative losses. The main reason is due to the high TFCI which amounts to

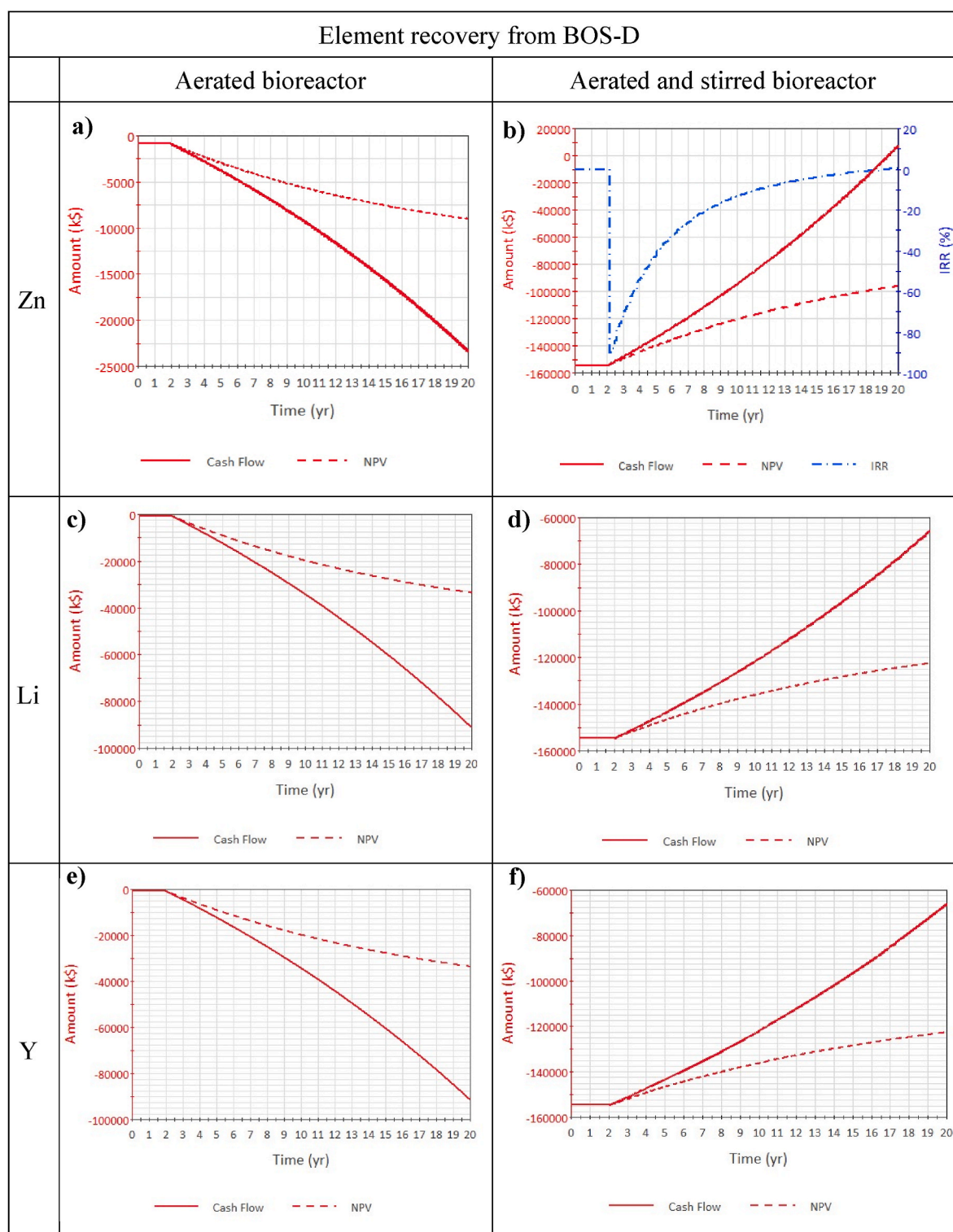


Fig. 3. Projection of cash flow, net present value (NPV) and internal rate of return (IRR) of Zn recovery from BOS-D over 20 years using aerated bioreactor (a) and aerated and stirred bioreactor (b), Li recovery using aerated bioreactor (c) and aerated and stirred bioreactor (d) and Y recovery using aerated bioreactor (e) and aerated and stirred bioreactor (f). Bioleaching condition was 10% PD, 2% energy source concentration, 1% inoculum concentration, pH 2.

\$154,460,499 (Table S12) for the aerated and stirred bioreactor plant and to \$782,466 for the aerated bioreactor plant (Table S13). This high TFCI significantly impacts potential profit since revenues are comparatively small.

4. Conclusion

Bioleaching of BOS-D revealed no estimated profits, whereas goethite bioleaching using aerated bioreactor for Cu (\$127.4M) and all nine elements (\$133.6M) resulted in profitable scenarios. In contrast, profits up to \$13M were forecasted when the aerated and stirred bioreactor plant was used to recover Cu from goethite with a 10% PD,

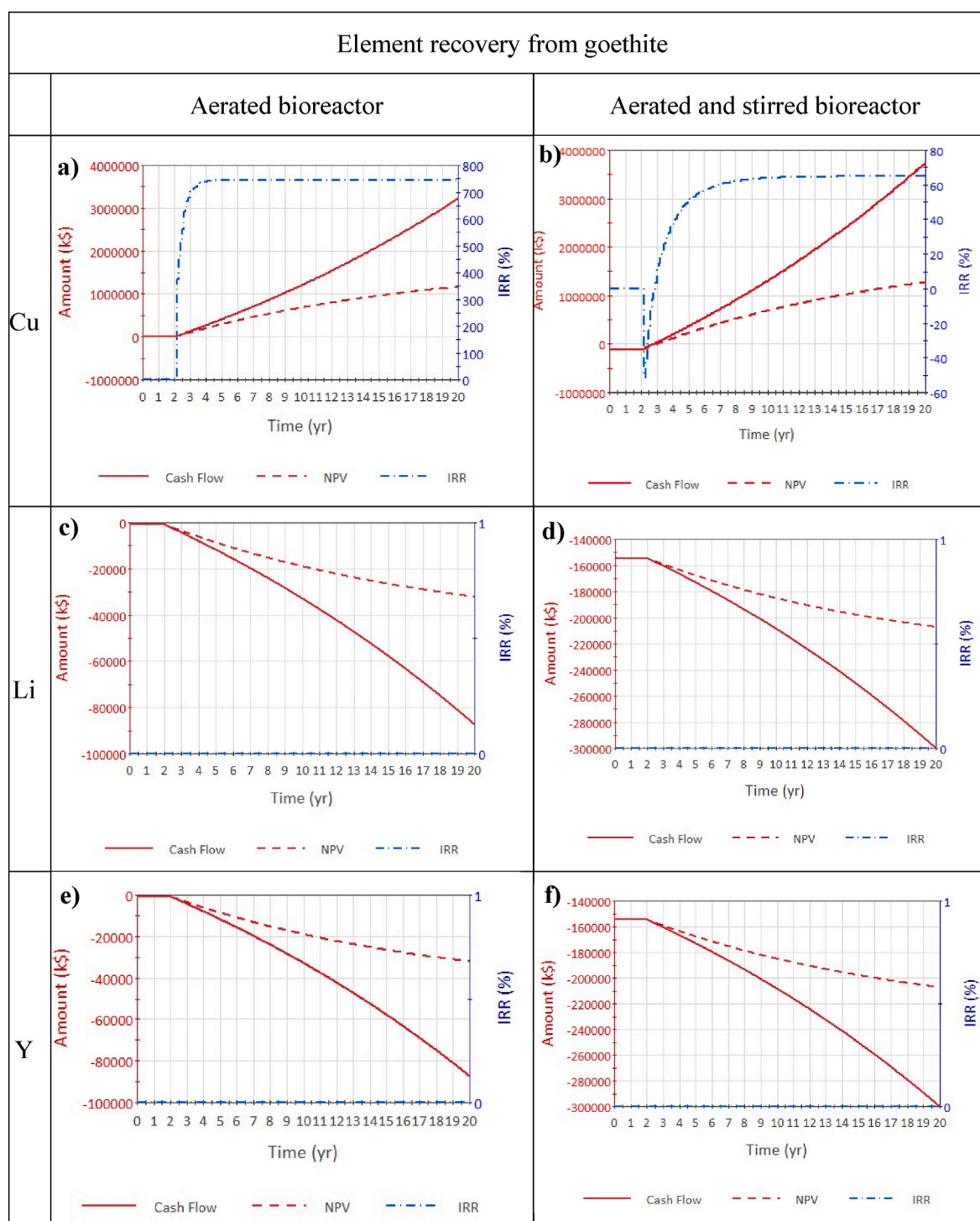


Fig. 4. Projection of cash flow, net present value (NPV) and internal rate of return (IRR) of Cu recovery from goethite over 20 years using aerated bioreactor (a) and aerated and stirred bioreactor (b), Li recovery using aerated bioreactor (c) and aerated and stirred bioreactor (d) and Y recovery using aerated bioreactor (e) and aerated and stirred bioreactor (f). Bioleaching condition was 10% PD, 3% energy source concentration, 1% inoculum concentration, pH 2.

3% energy source concentration, 1% inoculum concentration and pH 2. For this scenario financial analysis predicted a NPV of 1,275,499 k\$ and an IRR of 65% over 20-years after project started. It is expected that plant will start to make profit after one year of operations with a 119,816,550 \$ CAPEX and 5,896,580 \$/year OPEX. The aerated and stirred bioreactor can possibly provide better management and operation rather than aerated one as the plant consists of multiple reactors with small volumes. Personnel and electricity costs appeared as major expenses associated with the operation of the process.

CRediT authorship contribution statement

Ipek Tezyapar Kara: Writing – original draft, Investigation, Formal analysis, Conceptualization. **Stuart T. Wagland:** Writing – review & editing, Supervision, Resources, Conceptualization. **Frederic Coulon:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All the data supporting this study are included within the article and supplementary materials.

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Appendix A. Supplementary data

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Techno-economic assessment of bioleaching for metallurgical by-products

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