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Environmental and economic assessment of valuable component recovery from iron tailings

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Abstract: Iron tailings are among the largest industrial solid wastes in China, making their high-value utilization essential for sustainable resource management. This study evaluates the environmental and economic performance of an integrated recovery process for the comprehensive utilization of iron tailings, in which high-purity quartz sand, feldspar, and iron concentrate are simultaneously recovered. The system includes fine grinding, high-intensity magnetic separation, flotation, roasting, acid leaching, and wastewater treatment, with 1 ton of iron tailings selected as the functional unit. The LCA results indicate that primary energy demand (PED), water use (WU), global warming potential (GWP), and acidification potential (AP) represent the major environmental burdens, with characterization results of 2.72E+03 MJ, 4.76E+03 kg, 1.56E+02 kg CO_2 eq, and 6.18E-01 kg SO_2 eq, respectively. Hydrochloric acid and electricity were the major environmental hotspots, while tap water, oxalic acid, quicklime, and flotation reagents also contributed substantially to specific impact categories. The leaching stage was the dominant contributor to most environmental impacts. Sensitivity analysis identified electricity, hydrochloric acid, tap water, oxalic acid, and water-treatment chemicals as key parameters. The economic assessment showed that operating costs dominated the annual cost structure, with raw materials and utilities accounting for the largest shares. LCC sensitivity analysis identified flotation reagents, leaching acid, and electricity as the major cost drivers, while NPV was highly sensitive to the price of high-purity quartz sand. Overall, the integrated process shows potential for high-value iron-tailings utilization, while its economic performance remains sensitive to product prices and operating costs, providing a basis for process optimization.

Keywords: iron tailings, Life cycle assessment (LCA), Economic assessment, resource recovery, high-purity quartz sand

1. Introduction

Iron tailings are one of the largest bulk industrial solid wastes generated during iron ore beneficiation. In January 2026, the State Council of China issued the Action Plan for Comprehensive Solid Waste Management, emphasizing the coordinated reduction and high-value utilization of industrial solid wastes throughout the 15th Five-Year Plan period. Among these wastes, the annual generation of iron tailings exceeds 600 million tons, with accumulated stockpiles approaching 8 billion tons (Kinnunen et al., 2018). Long-term stockpiling not only occupies large areas of land but also poses potential environmental risks due to the release of residual heavy metals and alkaline substances (Psyrri et al., 2026). Therefore, developing efficient and sustainable resource utilization technologies for iron tailings has become an important strategy for promoting resource conservation, environmental protection, and circular economy development.

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In recent years, considerable efforts have been devoted to the high-value utilization of iron tailings (Liu et al., 2025). Previous studies have demonstrated that valuable mineral products, including quartz, feldspar, and iron concentrates, can be effectively recovered through integrated beneficiation technologies involving grinding, magnetic separation, flotation, and acid leaching (Li et al., 2024; Long et al., 2024). Existing research has mainly focused on improving mineral liberation efficiency, optimizing flotation reagent systems, enhancing impurity removal during acid leaching, and increasing product purity. These studies have confirmed the technical feasibility of producing high-value mineral products from iron tailings. However, most existing studies primarily evaluate separation efficiency and product quality, while the environmental burdens associated with intensive chemical consumption, electricity demand, and wastewater treatment are rarely quantified (Muñoz Morales et al., 2025). As the recovery process becomes increasingly complex, environmental and resource consumption issues may become key constraints affecting industrial-scale application.

Life cycle assessment (LCA) has been widely applied to evaluate the environmental performance of industrial solid waste utilization systems, including iron tailings-based construction materials, geopolymer production, and other mineral resource recovery processes (Guo et al., 2023). Meanwhile, economic assessment provides an effective framework for assessing the financial feasibility and economic performance of industrial processes by considering capital investment, operating costs, maintenance expenditures, and potential revenues (Wang et al., 2024; Lu et al., 2026). The integration of LCA and economic assessment has become an important approach for supporting sustainable process design and engineering decision-making.

Nevertheless, existing environmental-economic assessments mainly focus on low-value utilization pathways such as construction materials and backfilling, whereas studies on integrated recovery systems simultaneously producing quartz, feldspar, and iron-bearing products remain very limited. More importantly, the environmental hotspots, cost drivers, and potential trade-offs among multiple beneficiation and purification processes have not yet been systematically investigated from a life-cycle perspective.

Therefore, this study develops an integrated environmental–economic assessment framework for the comprehensive utilization of iron tailings by combining life cycle assessment (LCA) with economic assessment. Based on a functional unit of 1 ton of iron tailings, a life cycle inventory covering physical beneficiation, flotation, roasting, acid leaching, and wastewater treatment was established. The environmental impacts and economic performance of the integrated recovery process were quantified, and key environmental hotspots and economic drivers were identified through contribution and sensitivity analyses. The results provide a quantitative basis for further process optimization and the industrial utilization of iron tailings.

2. Materials and methods

This section describes the two methods used in this study: life cycle assessment (LCA) and economic assessment. It also describes how both methods were implemented.

2.1. Environmental analysis

2.1.1. Life cycle assessment

LCA is a tool for evaluating environmental elements and the potential impacts of a plethora of products and processes. As defined in the ISO 14040/14044 standards (ISO, 2006a; ISO, 2006b), LCA involves four stages: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and life cycle interpretation. The inputs and outputs were quantified within the goal and scope defined in the inventory analysis phase. Measurements or databases are used to quantify input parameters, such as energy and raw materials, and output parameters such as air pollutants and solid waste. In the impact assessment step, inventory results, such as greenhouse gas emissions, are tracked and converted into environmental impacts (i.e., climate change). Interpretation is the final step of the LCA and includes discussions and recommendations for improvement.

2.1.2. Goal and scope definition

This study focused on the purification and resource utilization process of iron tailings and established a “cradle-to-gate” life cycle assessment (LCA) model (Liu et al., 2022). The assessment covered the entire production system from tailings treatment to product output, including upstream processes such as electricity generation, chemical production (hydrochloric acid, oxalic acid, and flotation reagents), water supply, and chemical transportation, as well as the core purification processes and end-of-pipe treatment. The use and disposal stages of the resulting products were excluded. The system boundary is illustrated in Fig. 1. A functional unit of 1 ton of iron tailings treated was selected, and all material inputs, auxiliary materials, energy consumption, transportation activities, and direct emissions were quantified based on this functional unit. Since the primary objective of this study was to evaluate the environmental performance of iron tailings resource utilization rather than the production of individual products, the entire treatment system was considered as the evaluated system. The recovered quartz sand, feldspar, and magnetic products were regarded as co-products generated during the tailings purification process.

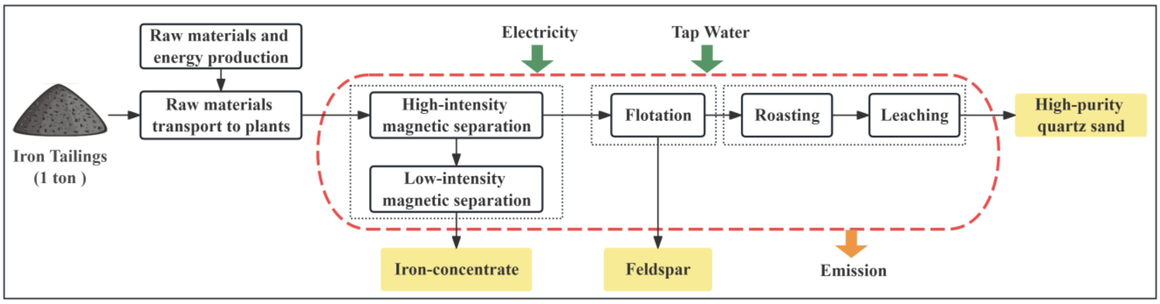

Fig. 1. System boundary of the comprehensive utilization of iron tailings

2.1.3. Process description

To characterize the resource composition and recovery potential of the iron tailings, Mineral Liberation Analysis (MLA) was conducted to determine the mineralogical composition of the raw tailings. Based on the identified mineral phases and their respective mineralogical abundances, the bulk chemical composition was calculated according to the stoichiometric composition of the constituent minerals, as summarized in Table 1. The detailed MLA-derived elemental composition, mineralogical composition, and particle-size characteristics are provided in the Supplementary Materials.

Table 1. Chemical composition of the iron tailings (wt %)

Component	SiO_2	Fe_2O_3	Al_2O_3	K_2O	Na_2O	MgO	CaO	SO_3	TiO_2	P_2O_5	MnO
Content (%)	68.61	12.12	9.08	3.78	1.61	2.01	2.04	0.39	0.23	0.07	0.06

As shown in Table 1, the tailings contained 68.61% SiO_2 and 12.12% Fe_2O_3, with quartz accounting for 41.23 wt%, albite 21.47 wt%, K-feldspar 12.33 wt%, olivine 9.97 wt%, and chlorite 6.81 wt%. Magnetite accounted for 1.23 wt%. The coexistence of abundant quartz and multiple impurity-bearing minerals necessitates the combined use of magnetic separation, flotation, and chemical leaching to obtain high-purity quartz.

This study adopted an integrated recovery process consisting of fine grinding, high-intensity magnetic separation (HIMS), low-intensity magnetic separation (LIMS), flotation, and roasting-acid leaching to achieve the comprehensive utilization of iron tailings (Gao et al., 2026). The process enabled the recovery of high-purity quartz sand, feldspar concentrate, and iron concentrate.The detailed process flow is illustrated in Fig. 2.

Initially, the iron tailings were mixed with water and subjected to preliminary screening. The oversize fraction was returned to the ball mill for further grinding to improve mineral liberation, while the undersize fraction proceeded to magnetic separation. Two-stage HIMS at approximately 14000 Oe was employed to remove magnetic impurities and reduce their interference with subsequent quartz-feldspar flotation. The tailings from the second HIMS stage were directed to flotation, whereas its concentrate was further treated by LIMS to recover iron-bearing minerals and produce an iron concentrate and residual LIMS tailings. The HIMS tailings were first subjected to flotation for further removal of residual iron-bearing impurities. The treated material was then subjected to selective flotation to separate quartz and feldspar. The rougher feldspar concentrate was subsequently re-floated for further purification, followed by dewatering and drying. The quartz concentrate was roasted at 1000 °C for 2 h using electric heating to promote the exposure of impurity phases and enhance subsequent leaching efficiency. After roasting, the material was rapidly quenched and then subjected to acid leaching using a mixed solution of hydrochloric acid, oxalic acid, and water to remove residual metallic impurities. The resulting high-purity quartz sand was recovered through solid-liquid separation, washing, and drying. Both flotation and acid-leaching wastewaters were treated by quicklime neutralization followed by PAC/PAM coagulation-sedimentation before discharge.

The specifications, particle-size ranges, and yields of the recovered products are summarized in Table 2. The high-purity quartz sand meets the specification of $SiO_2 \geq 99.9\%$ and $Fe_2O_3 \leq 100$ ppm, while the feldspar and iron concentrate satisfy their respective quality requirements. The combined yield of the three recovered products was 49.21%, with the remaining material accounted for in the life cycle inventory as tailings or other process outputs.

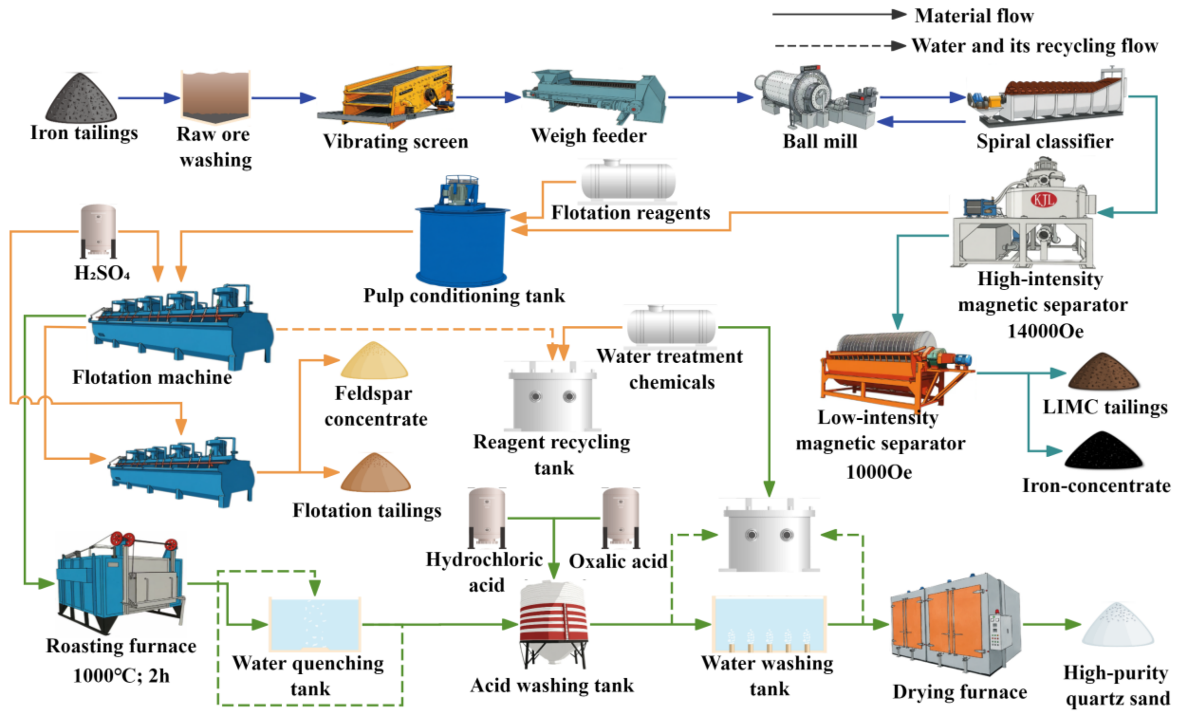

Fig. 2. Process flow of the comprehensive utilization of iron tailings

Table 2. Characterization and yields of the recovered products

Product	Quality specifications	Particle size	Yield
High-purity quartz sand	$SiO_2 \geq 99.9\%$; $Fe_2O_3 \leq 100$ ppm	200-400 mesh	18.80%
Feldspar	$Na_2O + K_2O \geq 8.5\%$; $Fe_2O_3 \leq 0.1\%$	200-325 mesh	28.60%
Iron concentrate	TFe ≥ 55%	-200 mesh≥96%	1.81%
Total	-	-	49.21%

Note: The total yield represents the combined yield of the recovered saleable products. The remaining material is accounted for separately in the life cycle inventory and is not included as a saleable product.

2.1.4. Life cycle inventory (LCI)

Life cycle inventory (LCI) analysis and reliable data collection are fundamental components of life cycle assessment (LCA). In this study, the LCI of the integrated recovery process was established based on enterprise data, measured data, and literature data. The detailed life cycle inventory is presented in Table 3. Background data, including electricity generation, raw material production, and chemical production, were mainly obtained from the Chinese Life Cycle Database (CLCD). For processes not available in the database, newly added processes were modeled using publicly available datasets or relevant data from the literature. Data selection followed the cut-off principle recommended by ISO 14040/14044. Material and energy flows with negligible contributions to the overall environmental impacts and limited influence on the impact ranking were excluded from the system boundary (Wang et al., 2024; Liu et al., 2022). Diesel consumption for short-distance internal transportation and lubricating oil used during equipment operation were excluded because their contributions were less than 0.1% of the total inputs. Iron tailings were treated as industrial solid waste entering the resource utilization system. Therefore, the environmental burdens associated with their original production and generation were not included, as these burdens had already occurred in the upstream industrial system.

Due to the lack of complete measured electricity data for the entire production line, total electricity consumption was estimated based on the energy consumption of comparable resource utilization and mineral processing processes. The electricity consumption was estimated at 68.7 kWh/t of iron tailings. Hydrochloric acid was used as a commercial solution with a concentration of 31 wt%, and the LCI was modeled using a dataset with the same concentration basis. Only fresh hydrochloric acid input was considered, while acid recovery and regeneration were not included. Chemical inputs were assigned to the corresponding process units according to their actual dosages. Due to the dispersed sources of raw materials and auxiliary chemicals, an average transportation distance of 50 km was assumed for externally supplied materials. Transportation was modeled using 30-ton diesel trucks (Liu et al., 2022), and transportation impacts were calculated according to the mass of transported materials and the assumed transportation distance.

To identify environmental hotspots, the integrated recovery process was divided into three major stages, namely physical beneficiation, flotation, and leaching. The physical beneficiation stage included screening, ball milling, and magnetic separation, the flotation stage consisted of flotation separation, and the leaching stage included roasting, water quenching, and acid leaching. Electricity consumption was allocated to the three stages at 50%, 15%, and 35%, respectively. Water consumption was allocated to the physical beneficiation, flotation, and leaching and post-treatment stages at 35%, 20%, and 45%, respectively. Chemical inputs and direct emissions were assigned to the process units where they were consumed or generated, while transportation burdens were allocated according to the mass of materials transported to each stage. The integrated recovery process produces three products, namely high-purity quartz sand, feldspar, and iron concentrate. As this study primarily focuses on the environmental impacts of iron tailings resource utilization, economic allocation was not applied. Environmental burdens were allocated according to the actual material, energy, chemical, and transportation inputs associated with each process stage.

The low-intensity magnetic separation tailings are not classified as a saleable product because no reliable market price was assigned to this material in the present economic assessment. However, this material is not regarded as a direct environmental emission or waste requiring disposal. It is retained in the material balance as a non-saleable secondary material and has potential for further utilization as a raw material in nearby building-material plants. To avoid overestimating the economic and environmental benefits, neither sales revenue nor environmental credits associated with its potential utilization are included in the present assessment.

2.1.5. Life cycle impact assessment (LCIA)

The eFootprint online analysis platform developed by IKE Environmental Technology Co. was used to perform quantitative analysis of the full life cycle process (IKE, 2015). The platform provides a globally unified and continuously updated database, including CLCD, ELCD, and Ecoinvent, which contains commonly used characterization factors, and normalized reference values for China's national conditions (Wang et al., 2011; Liu et al., 2022). To date, the eFootprint software has been widely adopted by many researchers. Considering the environmental characteristics of the integrated recovery process for comprehensive utilization of iron tailings and referring to relevant literature, nine environmental impact categories were selected for characterization analysis, including global warming potential (GWP)

Table 3. Life cycle inventory (LCI) of resource utilization scenarios for 1 ton iron tailings

Category	Item	Unit	Value	Data source	Upstream data
Resources and energy					
Transport	Diesel truck (30 t) transportation	km	50	Literature (Liu et al., 2022)	CLCD-2023 0.9.6
Raw materials	Iron tailings	kg	1000	Field survey	-
	Electricity	kWh	68.7		CLCD-2023 0.9.6
	Tap water	m^3	2.16		CLCD-2023 0.9.6
	Dodecylamine (DDA)	kg	2.32		Foreground process data
	Sodium dodecylbenzenesulfonate (SDBS)	kg	1.82		Foreground process data
	Sodium hexametaphosphate (SHMP)	kg	0.8		CLCD-2023 0.9.6
	Sodium petroleum sulfonate (SPS)	kg	0.66		Foreground process data
	Sulfuric acid (H_2SO_4)	kg	1.38		CLCD-2023 0.9.6
	Sodium hydroxide (NaOH)	kg	0.13		CLCD-2023 0.9.6
	Quicklime	kg	26.78		CLCD-2023 0.9.6
	Poly aluminium chloride (PAC)	kg	0.94		CLCD-China-ECER 0.8
	Polyacrylamide (PAM)	kg	0.04		CLCD-2023 0.9.6
	Hydrochloric acid (31wt%)	kg	94		CLCD-2023 0.9.6
	Oxalic acid	kg	5.64		CLCD-China 0.9.5
Products and emissions					
Main product	High-purity quartz sand (SiO_2≥99.9%; Fe_2O_3≤100ppm)	kg	188	Field survey	-
By-products	Feldspar (Na_2O+ K_2O≥ 8.5%)	kg	286		-
	Iron concentrate (TFe≥ 55%)	kg	18.12		-
Reusable secondary material	Low-intensity magnetic separation tailings	kg	434.88		
Solid waste	General industrial solid waste	kg	29.05		-
	Flotation tailings	kg	56		-
Hazardous waste	Waste oil and packaging drums	g	0.182		CLCD-2023 0.9.6
Environmental emissions	NH_3-N	g	1.75	Monitoring analysis	-
	SS	g	25		-
	H_2SO_4	g	0.018		-
	BOD	g	0.18		-
	Oil	g	0.313		-
	TN	g	1.60		-
	TSP	g	1.86		-
	TP	g	0.05		-
	COD	g	87		-
	HCl	g	153		-
	$H_2C_2O_4$	g	0.38		-

primary energy demand (PED), abiotic depletion potential (ADP), water use (WU), acidification potential (AP), eutrophication potential (EP), respirable inorganic particulate matter (RI), ozone depletion potential (ODP), and photochemical ozone formation potential (POFP). Based on the selected environmental impact categories, characterization analysis was performed to quantify the potential environmental impacts associated with the integrated recovery process (Lai et al., 2021). Subsequently, normalization analysis was conducted to facilitate comparison among different impact categories and identify the dominant environmental burdens.

2.1.6. Life cycle interpretation

The interpretation phase was conducted in accordance with the goal and scope of the study, focusing on identifying the major contributing factors and key inventory parameters influencing the environmental and life cycle cost performance of the integrated recovery process for comprehensive utilization of iron tailings. Sensitivity analysis was performed by varying material and energy inputs by ±5% (Liu et al., 2022), and the coefficient of variation was used to assess the robustness and reliability of the results (Gao et al., 2023). The findings were interpreted to support conclusions and provide recommendations for process optimization.

2.2. Economic assessments

2.2.1. System boundary and assumptions

A life cycle costing (LCC) approach was employed to evaluate the resource utilization costs associated with the integrated recovery process for iron tailings. The cost system boundary was consistent with that adopted in the LCA to ensure comparability between the environmental and economic assessments. It included iron tailings transportation, physical beneficiation, magnetic separation, flotation, roasting, acid leaching, and wastewater treatment processes (Cortés-Estrada et al., 2022; Croxatto Vega et al., 2020).

The LCC analysis was conducted based on an annual processing capacity of 400,000 t of iron tailings. The prices of chemicals and auxiliary materials were obtained from market data, and the selling prices of the recovered products were also determined based on market data. The market prices of high-purity quartz sand, feldspar, and iron concentrate were 176.47, 51.47, and 58.82 \$/t, respectively. Transportation costs were assigned to iron tailings transportation and off-site transportation of the recovered products, respectively. The iron tailings were assumed to be transported by road from a steel plant in eastern Hebei Province to the resource utilization facility over an average distance of 5 km, while the average off-site transportation distance of the recovered products was assumed to be 50 km. The project lifetime was assumed to be 15 years with a discount rate of 10%. Labor costs were estimated based on the average wage of urban non-private employees in Hebei Province in 2024, assuming a workforce of 96 employees. At the end of the project lifetime, the salvage value was assumed to be 5% of the combined investment in equipment procurement and installation, civil construction, and environmental protection facilities. Policy-related factors, including value-added tax, corporate income tax, government subsidies, and carbon trading benefits, were excluded to evaluate the intrinsic life cycle cost of the resource utilization process (Wang et al., 2024).

The life cycle cost mainly included the initial investment and the costs incurred during operation, including raw materials, energy, labor, transportation, maintenance, and management, while product sales revenues were excluded. In addition, net present value (NPV) was used to further evaluate the economic performance of the project by incorporating product sales revenues into the project cash flow. Annual product sales revenues were calculated based on the product yields reported above and the corresponding market prices. The NPV considered the initial investment, annual operating costs, product sales revenues, and terminal salvage value over the 15-year project lifetime at a discount rate of 10%.

2.2.2. Life cycle cost calculation

The fixed capital investment (FCI, \$) consists of equipment procurement, installation, plant building construction, environmental protection facilities, land cost, contingency cost and is calculated as follows:

$$FCI=DC_{equip}+DC_{inst}+DC_{plant}+DC_{env}+DC_{land}+DC_{cont} \quad (1)$$

Based on the FCI, the working capital (WC, \$) is evaluated as:

$$WC=wcc*FCI \quad (2)$$

where, wcc is the working capital coefficient. The total capital investment (TCI, \$) sums up the FCI and the WC :

$$TCI=FCI+WC \quad (3)$$

The ACC is defined as:

$$ACC=TCI\cdot\frac{r}{1-(1+r)^{-t}} \quad (4)$$

where r is the discount rate and t is the project lifetime. The total operating cost (TOC, \$/y), which is used to characterize all annual expenses incurred during project operation, is calculated by adding the raw material cost (RMC, \$/y), utility Cost (UC, \$/y), labor cost (LC, \$/y), equipment maintenance cost (EMC, \$/y), administrative Cost (AC, \$/y) and transportation cost (TC, \$/y).

$$TOC=RMC+UC+LC+EMC+AC+TC \quad (5)$$

The raw material cost is defined as:

$$RMC=\sum_j (Pr_j\cdot Q_j) \quad (6)$$

where Q_j is the annual consumption of the j-th raw material (ton/y). The utility cost (UC, \$/y) is calculated based on the annual electricity consumption and water consumption.

$$UC=Pr_{elec}\cdot W_{elec}+Pr_{water}\cdot F_{water} \quad (7)$$

where $P_{elec}$is the electricity price,W_{elec} is the electricity consumption, P_{water} is the water price, and F_{water} is the water consumption. The off-site transportation cost of iron tailings is estimated using the unit transportation cost method, which is a function of transportation volume and distance.

$$TC=M\cdot D\cdot ct \quad (8)$$

where M is the annual transportation volume (ton/year), D is the transportation distance (km), and ct is the unit transportation cost (\$/(ton·km)).

The total annual cost (TAC, \$/y) represents the annual cost of the integrated recovery process and is calculated as the sum of the annualized capital cost (ACC, \$/y) and the total operating cost (TOC, \$/y):

$$TAC=ACC+TOC \quad (9)$$

The life cycle cost (LCC) represents the total discounted cost incurred throughout the project lifetime and was used to evaluate the long-term cost characteristics of the integrated recovery process. It is calculated as follows:

$$LCC=FCI+TOC\times\frac{1-(1+r)^{-t}}{r}-S\times(1+r)^{-t} \quad (10)$$

where S is the salvage value at the end of the project lifetime, estimated based on the residual value of major equipment and facilities after deducting decommissioning costs.

2.2.3. Economic feasibility analysis

The total revenue (R, \$/y) of the project is composed of the sales revenue of each product, including high-purity quartz sand and by-products such as potassium-sodium feldspar and iron-bearing magnetic products.

$$R=\sum (P_i\cdot Q_i) \quad (11)$$

where P_i is the unit price of the i-th product (\$/t), and Q_i is the annual output of the i-th product (t/year). The annual net cash flow (CF, \$/year) is defined as the difference between the actual cash inflows and cash outflows of the project occurring within one year.

$$CF=R-TOC \quad (12)$$

The net present value (NPV, \$) is used to evaluate the economic benefits over the entire life cycle of the project and is defined as:

$$NPV=\sum_{t=1}^{n}\frac{CF_t}{(1+r)^t}-TCI+(S+wc)\times(1+r)^{-t} \quad (13)$$

where CFt is the net cash flow at year t. The internal rate of return (IRR) is the discount rate that makes the net present value equal to zero and is used to measure the level of investment return and is defined as:

$$NPV=0 \quad (14)$$

The dynamic payback period (PBP) is used to characterize the speed of investment recovery and is defined as:

$$PBP_d=-\frac{\ln\left(1-\frac{TCI\cdot r}{CF_{annual}}\right)}{\ln(1+r)} \quad (15)$$

3. Results

3.1. Environmental assessment results

3.1.1. Characterization analysis

The life cycle impact assessment (LCIA) results of the integrated recovery process for the comprehensive utilization of iron tailings are presented in Table 4. Overall, the process exhibited relatively high environmental burdens in terms of primary energy demand (PED), water use (WU), global warming potential (GWP), and acidification potential (AP). The PED and WU reached 2.72E+03 MJ and 4.76E+03 kg, respectively, while the GWP and AP were 1.56E+02 kg CO_2 eq and 6.18E-01 kg SO_2 eq. The characterized results for ADP, EP, RI, ODP, and POFP were 9.82E-04 kg antimony eq, 1.12E+00 kg PO_4^{3-} eq, 2.60E-01 kg $PM_{2.5}$ eq, 1.64E-06 kg CFC-11 eq, and 8.42E-02 kg NMVOC eq, respectively. These results indicate that energy and water consumption, together with the use of chemical reagents, are the major sources of environmental burdens in the integrated recovery process.

Fig. 3a presents the contribution of individual inventory items to the characterized environmental impacts. Electricity and hydrochloric acid were the major contributors to GWP, accounting for 27.31% and 27.12%, respectively. Hydrochloric acid was also the largest contributor to PED, with a contribution of 37.65%, followed by electricity at 19.03%. This can be attributed to the substantial energy requirements associated with hydrochloric acid production and electricity consumption during grinding, magnetic separation, flotation, and leaching. Tap water was the dominant contributor to WU, accounting for 47.27% of the total impact, followed by hydrochloric acid at 24.29%. The relatively high water demand was mainly associated with wet beneficiation, flotation, and acid leaching. AP was mainly contributed by hydrochloric acid, direct emissions, oxalic acid, and transportation, which accounted for 22.65%, 21.84%, 19.58%, and 12.01%, respectively. EP was dominated by direct emissions, contributing 76.25%, while oxalic acid accounted for 19.64%. Quicklime was the dominant contributor to RI, accounting for 74.62%, indicating that the production of quicklime represents an important source of particulate-related environmental burdens. Oxalic acid was the largest contributor to ODP, accounting for 57.74%, whereas transportation contributed 19.21%. For POFP, DDA was the largest contributor, accounting for 33.02%, followed by transportation at 26.60%. The individual flotation reagents showed distinct environmental profiles. Among them, SPS made a relatively important contribution to GWP and PED, while DDA exhibited a particularly high contribution to WU and POFP. SDBS and SHMP also contributed to several impact categories, although their contributions were generally lower than those of the major hotspots. Overall, hydrochloric acid, electricity, tap water, oxalic acid, quicklime, DDA, and other specific flotation reagents were identified as the major inventory-level environmental hotspots.

To further identify the environmental hotspots, the contributions of physical beneficiation, flotation, and leaching were compared in Fig. 3b. The leaching stage was the dominant contributor to most impact categories, accounting for 74.95% of GWP, 81.55% of PED, and 87.63% of AP, as well as substantial proportions of ADP, WU, EP, RI, and ODP. Flotation showed the highest contribution to POFP, accounting for 50.24%, whereas physical beneficiation generally showed lower contributions across the evaluated categories. The contribution analysis of individual stages is further presented in Fig. 3c–e. Electricity was the major contributor within physical beneficiation, while flotation showed distinct contribution patterns among the individual reagents. In the leaching stage, hydrochloric acid was the major contributor to GWP, PED, ADP, WU, and AP, whereas oxalic acid and quicklime showed relatively high contributions to selected impact categories.

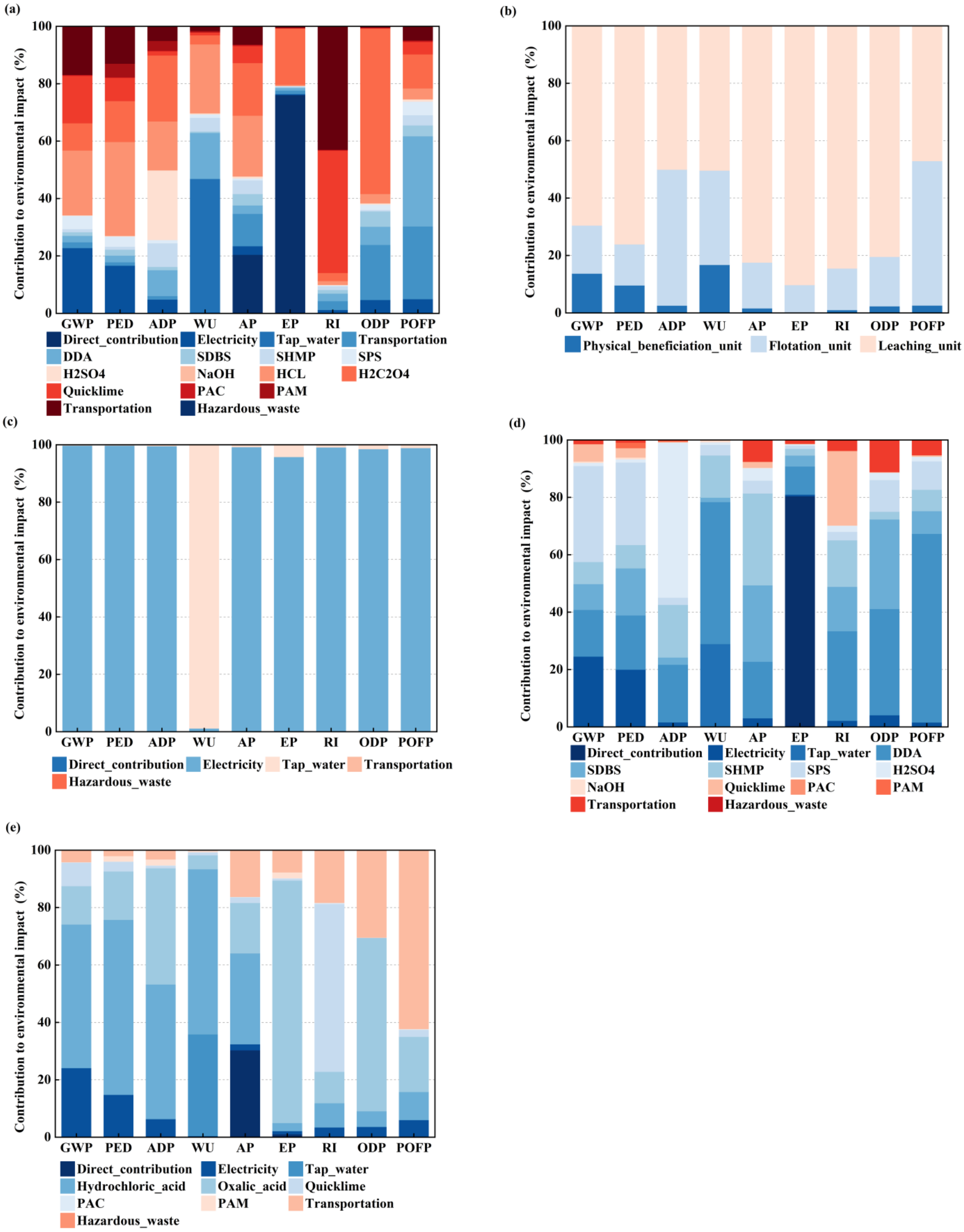

Fig. 3. Contribution analysis of environmental impacts: (a) contribution of different inventory items, (b) contribution of different process stages, (c) physical beneficiation stage, (d) flotation stage, and (e) leaching stage

3.1.2. Normalization analysis

Normalization expresses the characterized environmental impacts relative to regional reference values, thereby enabling comparisons among different impact categories and identifying the dominant environmental burdens (Liu et al., 2022). The normalization references were obtained from the 2020 Chinese life cycle environmental normalization database, which integrates data from the National Bureau of Statistics of China, the BP Statistical Review of World Energy, and the China Ecological and

Table 4. The results of Life cycle impact assessment (LCIA) characterization

Environmental Impact Indicator	Unit of measurement	LCA	Uncertainty	95% Confidence Interval
GWP	kg CO_2 eq	1.56E+02	3.73%	[1.50E+02, 1.62E+02]
PED	MJ	2.72E+03	3.13%	[2.63E+03, 2.80E+03]
ADP	kg antimony eq	9.82E-04	2.87%	[9.54E-04, 1.01E-03]
WU	kg	4.76E+03	6.58%	[4.45E+03, 5.07E+03]
AP	kg SO_2 eq	6.18E-01	2.61%	[6.02E-01, 6.34E-01]
EP	kg PO_4^{3-} eq	1.12E+00	3.30%	[1.08E+00, 1.16E+00]
RI	kg $PM_{2.5}$ eq	2.60E-01	8.21%	[2.39E-01, 2.81E-01]
ODP	kg CFC-11 eq	1.64E-06	2.96%	[1.59E-06, 1.69E-06]
POFP	kg NMVOC eq	8.42E-02	2.46%	[8.21E-02, 8.63E-02]

Environmental Statistics Annual Report (Chen et al., 2024). The normalized results are presented in Fig. 4a.

The normalized results reveal considerable differences among the environmental impact categories. Among the selected indicators, EP exhibits the highest normalized value, followed by AP and WU, whereas RI, PED, and GWP show comparatively lower normalized values. The normalized values of EP, AP, WU, RI, PED, and GWP are 4.62E-10, 1.94E-10, 4.62E-11, 4.25E-11, 1.86E-11, and 1.57E-11, respectively. Therefore, normalization shifts the emphasis from the absolute magnitude of the characterized impacts to their relative importance within the regional environmental context. In particular, eutrophication and acidification emerge as the most prominent environmental concerns, followed by water use and particulate matter-related impacts.

The cumulative normalized contributions of different inventory items are presented in Fig. 4b. When the normalized contributions across all impact categories are aggregated, direct emissions show the highest overall contribution, followed by oxalic acid and hydrochloric acid. Flotation and water treatment chemicals and quicklime also show relatively high cumulative contributions, whereas transportation, electricity, sulfuric acid, sodium hydroxide, and hazardous waste contribute less to the aggregated normalized burden. The high contribution of direct emissions is mainly associated with their influence on eutrophication and acidification, while the importance of oxalic acid is largely related to its contributions to EP and ODP. Hydrochloric acid contributes substantially across several impact categories, particularly PED, WU, and AP. By combining flotation reagents and water treatment chemicals into a single inventory group, their overall contribution becomes more apparent at the integrated process level. Overall, the normalized contribution analysis identifies direct emissions, oxalic acid, hydrochloric acid, flotation and water treatment chemicals, and quicklime as the principal inventory-level environmental hotspots.

Figures 4c-e present the normalized contribution analysis of the physical beneficiation, flotation, and leaching stages, respectively. Compared with the detailed characterization results, the normalized stage-level analysis provides a cross-category perspective on the relative importance of different process units. The physical beneficiation stage is mainly associated with resource and energy requirements, whereas the flotation stage is characterized by the combined environmental contribution of flotation and water treatment chemicals. The leaching stage shows a more pronounced chemical-related environmental burden, with hydrochloric acid and oxalic acid representing the major contributors. This stage-level differentiation indicates that the environmental hotspots are process-specific rather than governed by a single inventory item throughout the entire system.

3.1.3. Sensitivity analysis

To evaluate the influence of key parameter variations on the environmental impact results, representative environmental indicators, including GWP, PED, WU, AP, EP, and RI, were selected. A ±5% perturbation analysis was performed for key inventory parameters, including electricity, tap water, transportation, flotation reagents, hydrochloric acid, oxalic acid, and water treatment chemicals. The results are shown in Fig. 5, and the detailed data are provided in the Supplementary Information.

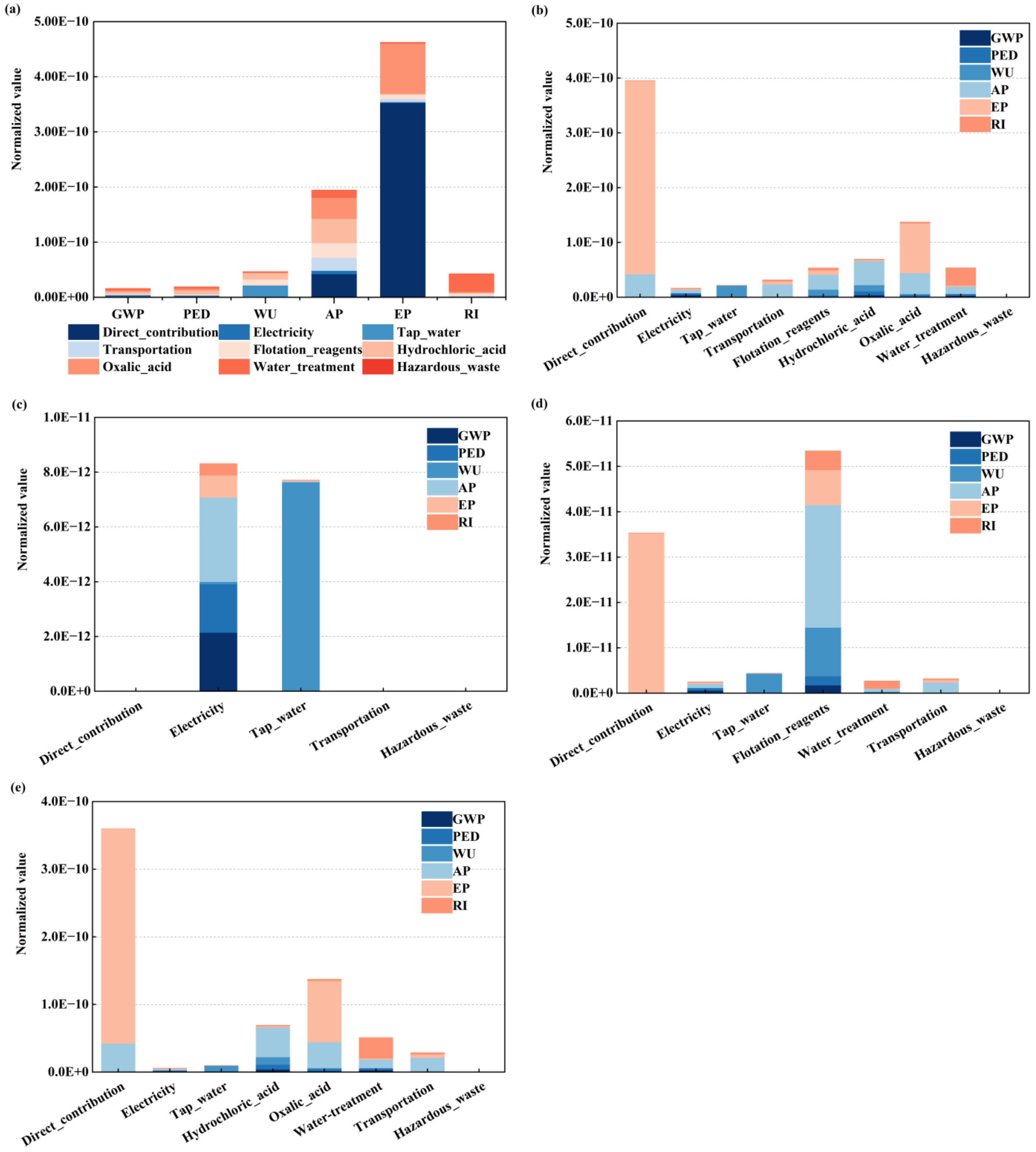

Fig. 4. Normalization analysis results: (a) normalized environmental impact categories, (b) cumulative normalized contributions of different inventory items, (c) physical beneficiation stage, (d) flotation stage, and (e) leaching stage

The sensitivity analysis indicates that the influence of key inventory parameters varies considerably among environmental impact categories. Electricity and hydrochloric acid showed the greatest effects on GWP, with a 5% reduction in their inputs resulting in decreases of 1.37% and 1.36%, respectively. Hydrochloric acid exhibited the highest sensitivity for PED, with a 1.88% reduction in the corresponding impact. Tap water had the strongest influence on WU, resulting in a 2.36% decrease. For AP, hydrochloric acid showed the greatest effect, with a 1.13% reduction. Oxalic acid was the most influential parameter for EP, leading to a 0.98% decrease, whereas water treatment chemicals exhibited the highest sensitivity for RI, with a 3.77% reduction. In comparison, transportation generally showed relatively limited effects on the selected environmental indicators, while flotation reagents had moderate effects on several impact categories. Overall, electricity, hydrochloric acid, tap water, oxalic acid, and water treatment chemicals were identified as the key parameters governing the environmental performance of the process. These results indicate that optimizing electricity consumption, acid dosage, water use, and water treatment chemical inputs would be particularly important for improving the environmental robustness of the process.

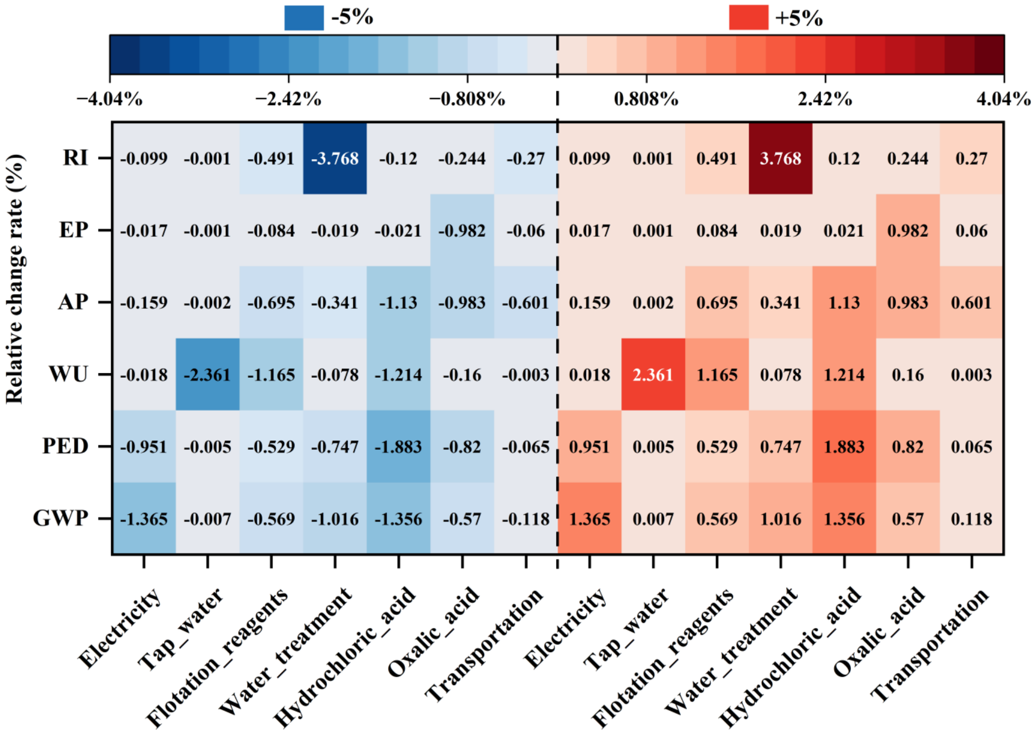

Fig. 5. Sensitivity analysis of environmental impacts

3.1.4. Uncertainty analysis

Uncertainty analysis was conducted to evaluate the data quality of the life cycle inventory, and the uncertainty levels together with the corresponding 95% confidence intervals are presented in Table 2. Overall, the uncertainty values of all environmental impact categories remained relatively low, ranging from 2.61% to 8.21%, indicating good data quality and satisfactory reliability of the life cycle inventory. Among the evaluated indicators, RI exhibited the highest uncertainty at 8.21%, followed by WU at 6.58% and GWP at 3.73%, whereas AP showed the lowest uncertainty at 2.61%. The corresponding 95% confidence intervals were relatively narrow across all impact categories, further indicating that the calculated environmental impacts were based on a consistent and reliable inventory dataset.

3.2. Economic assessment results

3.2.1. Economic performance and cost results

The capital investment and cost structure of the iron tailings resource utilization process were analyzed under the baseline scenario (Wang et al., 2024). The fixed capital investment (FCI) was estimated at approximately 17.65 million USD. With working capital assumed as 10% of the fixed capital investment, the total capital investment (TCI) was calculated to be approximately 19.41 million USD.

The annual cost composition of the integrated recovery process is presented in Fig. 6. The total annual cost (TAC) was estimated at approximately 18.02 million USD, consisting of the annualized capital cost (ACC) and total operating cost (TOC). The ACC was approximately 2.55 million USD, accounting for 14.15% of the TAC, while the TOC reached approximately 15.47 million USD, contributing 85.85% of the total annual cost. This result indicates that operational expenditures represent the dominant component of the annual cost structure. The TOC consisted of raw material cost (RMC), utility cost (UC), labor cost (LC), equipment maintenance cost (EMC), administrative cost (AC), and transportation cost (TC). Considering the overall annual cost, raw material consumption was the largest contributor, accounting for 47.07% of the TAC, followed by utility consumption with a contribution of 18.70%. Among individual cost items, flotation reagents and leaching acid were the two dominant contributors, accounting for 22.03% and 18.09% of the TAC, respectively. Electricity consumption represented another major cost component, contributing 15.26% of the TAC, which was mainly associated with the energy requirements of grinding, magnetic separation, roasting, and acid leaching processes. The calculated life cycle cost (LCC) was approximately 22.52 USD per ton of iron tailings, while the unit treatment operating cost was approximately 38.68 USD per ton of iron tailings. It should be noted that the unit treatment operating cost and unit life cycle cost (LCC) are based on different accounting boundaries. The former reflects the annual operating expenditure, whereas the latter accounts for the total cost over the project lifetime and is used to evaluate long-term cost performance. Under the baseline scenario, the project NPV was approximately 12.06 million USD, with an IRR of 20.95% and a discounted payback period (PBPd) of approximately 6.70 years. Overall, the baseline scenario indicates favorable economic performance without considering taxes or policy subsidies. The high added value of high-purity quartz sand is the main contributor to project profitability, while the recovery of feldspar and iron concentrate further enhances resource utilization.

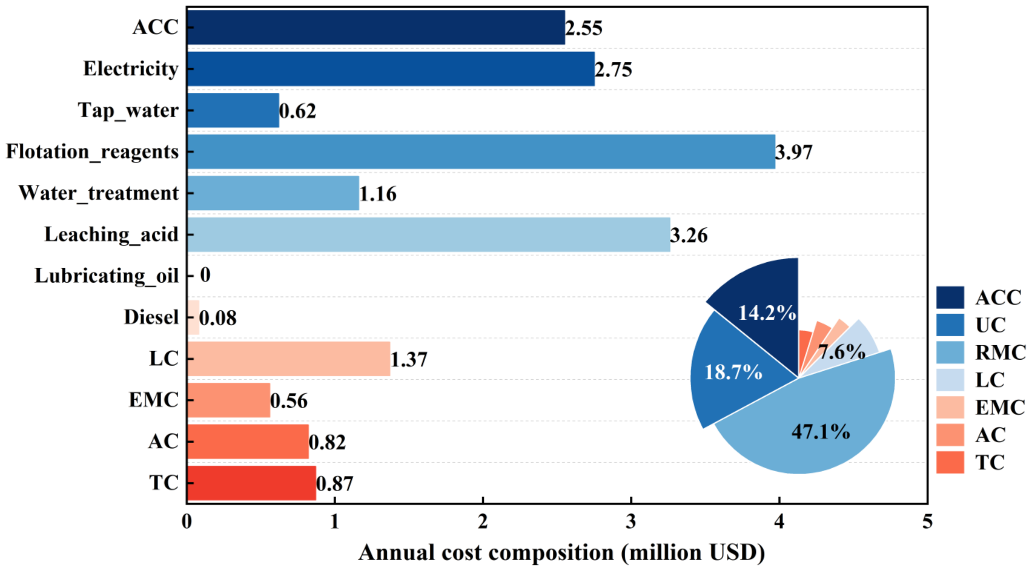

Fig. 6. Annual cost composition

3.2.2. Sensitivity analysis

The LCC sensitivity analysis results are presented in Fig. 7a. The results show that the lifecycle cost is mainly influenced by operating-related inputs, while the impact of fixed capital investment is relatively limited. Among all evaluated parameters, flotation reagent cost exhibited the highest sensitivity, with a ±20% variation leading to a 4.47% change in LCC. Leaching acid and electricity costs showed relatively high sensitivities, resulting in LCC variations of 3.67% and 3.09%, respectively. The fixed capital investment exhibited a moderate influence, with a 2.58% change in LCC under the same variation range. In contrast, tap water and water treatment costs had negligible effects, with LCC variations of only 0.70% and 1.31%, respectively. These results indicate that life cycle cost is more sensitive to changes in operating inputs than to capital investment, highlighting the importance of process optimization for long-term economic performance.

For NPV (Fig. 7b), the sensitivity analysis considered variations in product prices, including high-purity quartz sand, feldspar, and iron concentrate, as well as the costs of electricity, tap water, flotation reagents, water-treatment chemicals, and leaching acid. The results show that NPV is most sensitive to the price of high-purity quartz sand. A 20% increase in the price of high-purity quartz sand results in a 161.78% increase in NPV, whereas a 20% decrease causes NPV to become negative, indicating that the project may become economically infeasible under unfavorable market-price conditions. Further break-even analysis indicates that the project reaches the economic break-even point when the price of high-purity quartz sand decreases by 12.36% to 154.65 USD per ton, resulting in an NPV of zero. The price of feldspar is the second most influential product-related factor, with a 20% increase resulting in a 71.78% increase in NPV. In contrast, the effect of iron-concentrate price is relatively limited, with a 20% increase resulting in only a 5.20% increase in NPV. Among the cost factors, flotation reagents have the greatest influence, with a 20% increase in their price reducing NPV by 48.43%, followed by leaching acid, electricity, water-treatment chemicals, and tap water, which reduce NPV by 39.77%, 33.50%, 14.18%, and 7.59%, respectively. Overall, the economic performance of the process is primarily controlled by the market prices of the recovered products and the costs of flotation reagents and leaching chemicals, whereas tap-water costs have a comparatively minor effect on NPV.

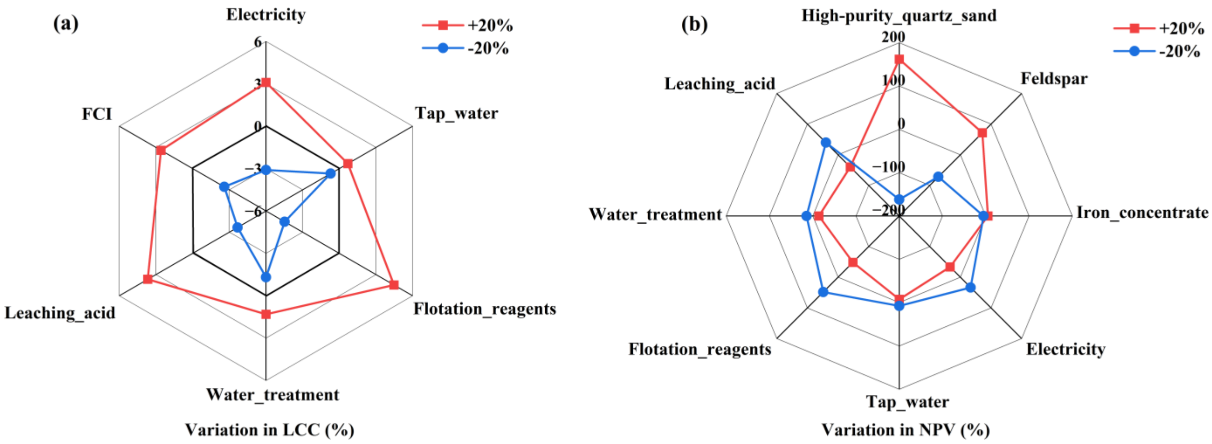

Fig. 7. Sensitivity analysiss: (a) Variation in LCC; (b) Variation in NPV

4. Discussion

4.1. Environmental impact mechanisms and optimization strategies

The environmental performance of the proposed iron tailings resource utilization process differs from that of conventional tailings utilization pathways. Previous studies on geopolymers, permeable bricks, and ceramsite have generally identified cement production, natural gas combustion, or high-temperature sintering as the main environmental hotspots (Guo et al., 2023; Lu et al., 2026). In contrast, the present process recovers high-value quartz, feldspar, and iron-concentrate through integrated beneficiation and purification, shifting the major environmental burdens toward chemical consumption and electricity use. This difference reflects the higher processing intensity required to achieve high product purity and indicates that environmental optimization should consider chemical efficiency as well as energy efficiency.

Hydrochloric acid was the dominant contributor to several impact categories, particularly GWP, PED, WU, AP, and ADP. This is mainly associated with the relatively high acid demand for impurity removal and the upstream environmental burdens of acid production. During leaching, hydrochloric acid dissolves impurity-bearing minerals and removes elements such as Fe, Al, Ca, and Mg from the quartz concentrate (Li et al., 2024; Meng et al., 2026). The resulting chloride-containing wastewater also requires treatment, further increasing chemical consumption. Therefore, reducing acid demand and improving acid utilization efficiency are important for environmental improvement. Acid regeneration and recycling could reduce fresh acid consumption, but their practical application may be limited by the complexity of the leaching solution and the additional equipment, energy, and separation requirements (Grison et al., 2025). Alternative leaching systems, such as deep eutectic solvents and recyclable organic leaching agents, may also provide potential pathways, although their environmental and industrial feasibility requires further verification through large-scale LCA (Hayyan et al., 2025; Yang et al., 2024; Faria-Júnior et al., 2025).

Electricity consumption was another important hotspot, particularly for GWP and PED, mainly due to grinding, magnetic separation, flotation, and roasting. Fine grinding is energy-intensive because adequate mineral liberation is required for subsequent separation; however, excessive grinding beyond the optimum liberation size may increase energy demand without proportional benefits to product quality. Therefore, optimization of grinding and classification conditions and the use of energy-efficient equipment could improve environmental performance without compromising mineral recovery. Increasing the use of renewable electricity could further reduce indirect greenhouse gas emissions (Xi et al., 2025). Water consumption also represents an important environmental concern because flotation and acid leaching are water-intensive operations. Although wastewater recycling is incorporated into the process, freshwater is still required to compensate for losses during solid–liquid separation and wastewater treatment. The dissolved salts and residual chemicals in leaching wastewater may also limit direct reuse (Lin et al., 2020). Improving closed-loop water management, staged reuse, and solid–liquid separation efficiency could therefore reduce freshwater demand and treatment requirements.

The relatively high normalized values of EP, AP, and WU may be partly related to the environmental characteristics reflected in the Chinese regional reference context, particularly pollution emissions and water resource use. However, these results are also influenced by the specific process inventory and normalization reference (Chen et al., 2024). Thus, the normalized results should be interpreted as reflecting both the characteristics of the recovery process and the regional context used for normalization. Environmental improvement should also consider trade-offs between resource consumption and process performance. Excessive reductions in acid dosage or grinding intensity may decrease environmental burdens but could impair impurity removal, mineral liberation, and product recovery (Li et al., 2024; Long et al., 2024). Therefore, future optimization should seek a balance between environmental performance, process efficiency, and product quality rather than minimizing individual inputs.

Finally, potential environmental risks associated with the treated tailings residue should be considered. Although the residual tailings are transported to cement and other building-material facilities for further utilization rather than directly disposed of within the study system, contaminant release under improper management may pose risks to soil and groundwater. These potential long-term impacts were not quantified within the cradle-to-gate boundary. Residue characterization and leaching tests should therefore be conducted in practical applications to verify its suitability for subsequent utilization.

4.2. Economic drivers and improvement strategies

The life cycle costing results indicate that operating costs are the dominant component of the economic performance of the integrated recovery process, with flotation reagents, hydrochloric acid, and electricity representing the major cost drivers. This cost structure is consistent with the environmental assessment, in which chemical consumption and energy use are also major hotspots. Compared with conventional tailings utilization pathways that mainly produce low-value construction materials, the proposed process involves multiple beneficiation and purification stages to obtain high-value quartz, feldspar, and iron-bearing products, resulting in higher processing intensity and operating costs. Therefore, improving reagent and energy efficiency is important for simultaneously reducing environmental burdens and life cycle costs (Wang et al., 2024).

The sensitivity analysis further indicates that operating costs have a greater influence on LCC than fixed capital investment, with flotation reagents, leaching acid, and electricity identified as the most sensitive cost parameters. This result highlights the importance of controlling variable operating costs for improving the long-term economic performance of the process. In particular, fluctuations in reagent and energy prices may substantially affect the overall life cycle cost, indicating that stable supply and cost-efficient procurement of major operating inputs are important for future industrial implementation.

The NPV sensitivity analysis highlights an additional economic risk associated with market fluctuations. The price of high-purity quartz sand was the most influential parameter, and the identified break-even price indicates that project profitability is particularly dependent on the market value of the main recovered product. Although product revenues were not included in the LCC calculation to avoid uncertainty from fluctuating market prices, the NPV analysis demonstrates that market conditions should be explicitly considered in future techno-economic assessments. Integrating product price dynamics with resource recovery efficiency, carbon pricing, and policy incentives would provide a more comprehensive assessment of the long-term economic feasibility of integrated iron tailings utilization.

5. Conclusions

This study established an integrated environmental-economic assessment framework combining life cycle assessment (LCA) and economic assessment to assess the comprehensive recovery of high-purity quartz sand, feldspar, and iron-bearing products from iron tailings. Based on a functional unit of 1 ton of iron tailings, the proposed process was systematically evaluated in terms of environmental performance, economic performance, and key influencing factors.

The environmental assessment showed that primary energy demand, water use, global warming potential, and acidification potential were the major impact categories. The acid leaching stage was identified as the principal environmental hotspot, mainly due to the intensive consumption of hydrochloric acid and oxalic acid. Electricity, hydrochloric acid, water consumption, and selected flotation and water-treatment chemicals were also important contributors to the overall environmental impacts. Sensitivity analysis further identified hydrochloric acid, electricity, tap water, oxalic acid, and water-treatment chemicals as key parameters affecting environmental performance, while the relatively low uncertainty levels indicated acceptable reliability of the inventory results. The economic assessment showed that operating costs represented a major component of the annual production cost, with flotation reagents, leaching acids, and electricity being the main cost drivers. The calculated life cycle cost (LCC) and economic performance indicators demonstrated the overall economic performance of the proposed process. Sensitivity analysis indicated that variable operating costs had a greater influence on LCC than fixed capital investment, whereas the NPV analysis showed that project profitability was particularly sensitive to the market price of high-purity quartz sand. These findings highlight the importance of controlling major operating costs and managing market-price risks in the future industrial implementation of the process.

Compared with conventional iron tailings utilization pathways that mainly produce single low-value construction materials, the proposed process enables the coordinated recovery of quartz, feldspar, and iron-bearing products, thereby improving the resource utilization efficiency and value potential of iron tailings. Overall, the integrated environmental-economic assessment framework provides a quantitative basis for identifying environmental and economic hotspots and supports process optimization and industrial decision-making for the high-value utilization of iron tailings.

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