minerals

MDPI

Article

Comparative Life Cycle Assessment of Conventional and Dry Stack Tailings Disposal Schemes: A Case Study in Northern China

Kun Wang [1,*], Zheng Zhang [1], Liyi Zhu [2,3], Xiuzhi Yang [1], Miao Chen [1] and Chao Yang [2]

[1] College of Energy and Mining Engineering, Shandong University of Science and Technology, Qingdao 266590, China
[2] School of Civil and Resource Engineering, University of Science and Technology Beijing, Beijing 100083, China
[3] Department of Chemical and Materials Engineering, University of Alberta, Edmonton, AB T6G 2V4, Canada
* Correspondence: kwang@sdust.edu.cn

Abstract: Alternative tailings disposal technologies can be effective solutions to mining waste safety and environmental problems. The current decision-making processes for tailings disposal schemes lack consideration of environmental impacts. Based on a case study of an open-pit iron mine in northern China, this study adopted the life cycle assessment (LCA) method to compare the environmental impacts of three tailings disposal schemes of conventional slurry disposal technology (CSDT), dry stack disposal technology (DSDT) by belt conveyance and DSDT by truck transport. The results indicated that (1) the environmental impacts of the CSDT scheme were lowest under the premise that water consumption was ignored; (2) the environmental impacts of the DSDT scheme by belt conveyance mainly originated from its transport process, indicating that the tailings storage facilities (TSFs) site planning could be crucial in design decision making; (3) the environmental impacts of the DSDT scheme by truck transport mainly originated from the energy consumption of dry stacking equipment; and (4) the DSDT scheme by truck transport was eventually found to be preferable and implemented in the case study, after comprehensively considering the LCA results, TSF safety and remaining capacity, and social and policy uncertainties. It is therefore recommended to conduct LCA of environmental impacts in the decision-making process for the sustainable design of TSFs.

Keywords: life cycle assessment; tailings disposal; conventional slurry disposal; dry stack tailings disposal; open pit mine

Citation: Wang, K.; Zhang, Z.; Zhu, L.; Yang, X.; Chen, M.; Yang, C. Comparative Life Cycle Assessment of Conventional and Dry Stack Tailings Disposal Schemes: A Case Study in Northern China. *Minerals* **2022**, *12*, 1603. https://doi.org/10.3390/min12121603

Academic Editor: Mostafa Benzaazoua

Received: 23 September 2022
Accepted: 13 December 2022
Published: 14 December 2022

1. Introduction

Mine waste tailings are the unwanted and currently uneconomical materials left after mineral processing involving the separation of valuable elements from ores [1]. Globally, tailings consistently comprise the major waste stream in the mining industry. Choosing China as an example, over the five years between 2016 and 2020, ore production increased by 22.3%, from 7.60 billion tons to 9.29 billion tons. The mined-out grade of most ores over the last decade has decreased [2]. For example, the underground mined-out grade of iron ores decreased by 4.6%, and the open pit mined-out grade decreased by 2.0%. Consequently, the annual tailings disposal amount remains over 1.2 billion tons (1.27 billion tons in 2019) [3]. The total disposed tailings amount reached over 20 billion tons, covering an area of 650 km^2. Despite the ongoing efforts of underground tailings backfilling, building material use and other tailings use schemes [4–6], nearly 70% of the produced tailings are still discharged into TSFs [3].

TSFs are essential facilities in the mining industry and are usually built with the inclusion of one or more dams for the purpose of containing mine waste tailings. In contrast to water retaining dams, tailings dams are mostly built using tailings themselves to control costs, but along with this comes a higher risk of dam breach accidents [7–9]. Recent examples [10–12] include the 2019 Brumadinho dam breach accident (12 million m^3 of released tailings and more than 249 deaths), the 2015 Fundão dam breach accident (32 million m^3 of released tailings and more than 17 deaths) and the 2014 Mount Polley dam breach accident (24.4 million m^3 of released tailings and water). China contains the most TSFs of any country in the world. A total of 7800 TSFs had been documented up until the end of 2020. Of these, over 70% were built using conventional slurry disposal technology (CSDT). According to the International Commission on Large Dams (ICOLD) and the United Nations Environment Programme (UNEP), the lack of water phreatic line control in CSDT-based TSFs is the main cause of dam breach accidents [13,14]. Moreover, with improvements in mining processing technology and equipment, finer-particle-size tailings are discharged, placing higher requirements on CSDT water phreatic line management.

Therefore, it is vital to implement alternative tailings disposal technologies, such as thickened tailings disposal technology (35~55% water content), paste tailings disposal technology (25~35% water content), or dry stack disposal technology (DSDT) (<25% water content) [15–19]. DSDT is a state-of-the-art technology that can process tailings streams into moist solid soils, which are then stacked in piles and compacted, rather than CSDT, which can process tailings streams with a water content that is normally higher than 70% [20,21]. However, the current decision-making processes for tailings disposal schemes lack consideration of environmental impacts.

In this study, the novel life cycle assessment (LCA) method was used to compare the environmental impacts of CSDT and DSDT schemes based on a case study of an iron mine in northern China. The results could be significant for stakeholders in implementing safer and more sustainable tailings disposal schemes.

2. Materials and Methods

2.1. Engineering Background

The open pit iron mine in the case study was established in 1968 and located in Qianan, Hebei Province, northern China. The annual average temperature is 11.9 °C. In addition, the minimum and maximum extreme recorded temperatures are −17 °C and 38 °C, respectively. The annual total precipitation is 639 mm. The mine is one of the largest open pit iron mines in China, with an annual ore production of 9 million tons. The amount of mined-out ores until 2020 reached 350 million tons. The annual tailings disposal amount was 7.7 million tons. The linear distance from the processing plant to the TSF is approximately 2.85 km, with a height difference of 115 m. A residential area is located only 0.8 km downstream of the TSF, which could be dangerous if a potential tailings dam breach occurred under extreme conditions such as earthquakes or floods. Moreover, based on its remaining capacity of 10.9 million m^3, the TSF can only be used for 3.68 years with the ongoing CSDT scheme, making this an extremely urgent issue for continuous mining production. It is, therefore, crucial to study the feasibility of using the DSDT scheme instead for safer operating conditions and lower land occupation.

2.2. Tailings Disposal Schemes

2.2.1. Conventional Slurry Disposal Technology (CSDT)

CSDT remains the main method of tailings waste disposal in the global mining industry due to the simplicity of the process and low initial construction investment [22,23]. A CSDT flowchart is shown in Figure 1. Tailings are produced from iron ores after a series of mineral processes. The tailings slurry is pumped directly at a low concentration (approximately 40%) through a pipeline to the TSF. Auxiliary machinery is used to assist tailings spreading after tailings deposition and stratification. Overflow clarified water and seepage clarified wastewater are pumped back to the processing plant for recycling through a water return system.

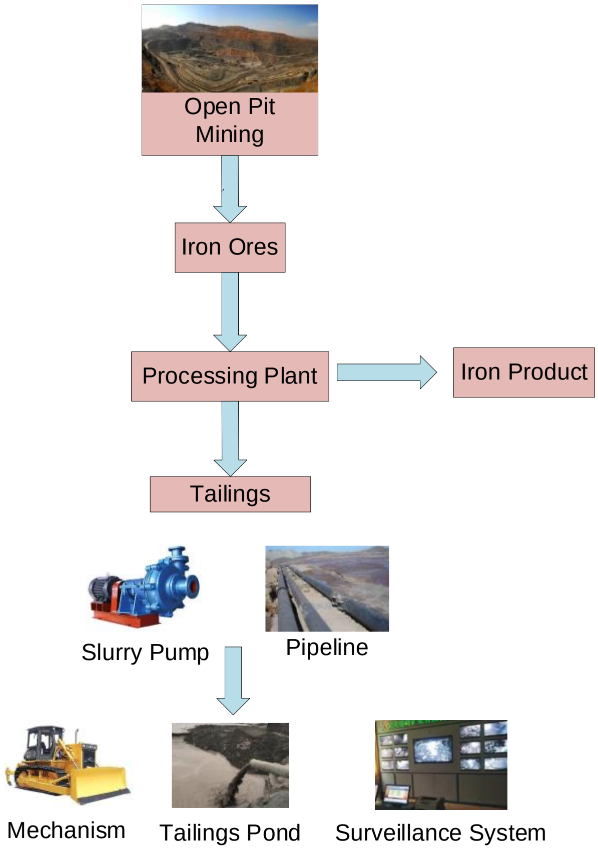

Figure 1. Flowchart of conventional slurry disposal technology (CSDT).

2.2.2. Dry Stack Disposal Technology (DSDT)

DSDT is a state-of-the-art technology that has seen rapid development in recent years. The tailings slurry stemming from the mineral processing output is discharged at a very low moisture content (<25%) and a high degree of solidification stacking after a series of processes, such as cyclone classification, thickening, filter pressing, and dewatering via a vibratory sieve [24]. Dry stacks are discharged by belt conveyance or truck transport and stockpiled in TSFs. DSDT tailings do not exhibit natural mobility, and no free water is stored under non-flood operating conditions, which fundamentally solves the challenge of phreatic level management [21,25]. Due to the high wastewater recovery rate, low water content in tailings, high degree of consolidation, and more stable mechanical properties of the pile, DSDT is considered to provide better safety and environmental performance. In China, DSDT was first practiced, achieving satisfactory results, in the Guilaizhuang gold mine in Shandong Province in 1994, and was subsequently applied in Inner Mongolia, Hunan, and Jiangxi Province.

Based on the slurry concentration and particle size of the output tailings material, the DSDT flowchart was designed, as shown in Figure 2.

High-water-content tailings slurry originating from iron ore processing is pumped to a cyclone unit, where the coarse-particle tailings slurry is treated by the cyclone and discharged from the bottom flow outlet, while fine-particle tailings are discharged from the upper overflow outlet by the centrifugal negative pressure of the cyclone. The high-concentration coarse-particle slurry is then pumped into a high-frequency vibrating dewatering sieve, forming a solid filter layer with a very low water content for discharge. While fine-particle tailings from the cyclone overflow enter the thickener to settle and thicken, the bottom flow is treated by a filter press and then subjected to dry stack treatment, and the overflow water experiences a series of processes such as sedimentation and filtration and is returned to the processing plant for recycling. Dry stacks are usually transported by truck or belt depending on the transport distance and terrain characteristics, and auxiliary machinery is needed to assist in the maintenance of the dry discharge tailings pile during operation.

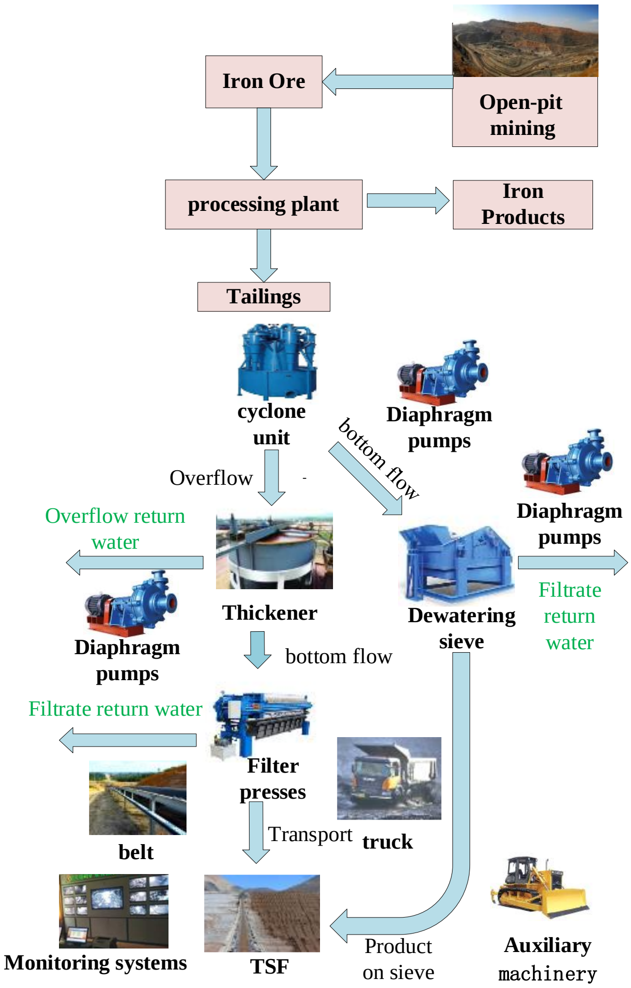

Figure 2. Flowchart of dry stack disposal technology (DSDT).

2.3. LCA Method

2.3.1. Introduction of LCA Method

LCA is an internationally standardized method for the analysis of the impacts associated with the entire cradle-to-grave life cycle of a product or service, from acquisition and processing of raw materials through manufacturing, production and packaging, transportation and sales, use and maintenance, recycling, and final disposal [26,27]. It is a standard method for quantifying and systematically evaluating the combined environmental impacts of products, processes, or services, with the aim of determining ways to reduce environmental impacts and developing measures for improvement [28,29]. LCA was first proposed in the late 1960s and early 1970s and gained widespread attention and rapid development in the late 1980s. Today, after more than 50 years of exploration and development, LCA is considered one of the most effective methods for evaluating the environmental impact of products, and is widely used in various decision-making and strategic planning processes [30]. As a much criticized and highly environmentally polluting industry, mining represents a promising application area for LCA [31–33]. However, current research mainly focuses on the environmental impact of the production process from ore mining to mineral processing and mineral products [34,35], often simplifying or ignoring the large amount of tailings waste disposal. Beylot and Villeneuve [36] studied the full life cycle impacts of the storage process of sulphide copper mine tailings waste discharge using a tailings pond in southwestern Poland as a case study and demonstrated that the environmental impacts of tailings discharge dominated the process flow of copper concentrate production and that tailings treatment should receive sufficient attention.

2.3.2. Objectives and Scope Definition

In previous studies on tailings waste, the tailings environmental impact had been addressed in two ways [37]. First, seepage into soil and groundwater systems occurred during daily operations, and the dispersal of pollutants in water systems occurred through surface runoff and into the atmosphere through dust. Second, immediate pollution was caused on short time scales (hours and months) following a dam breach, and ongoing pollution occurred on longer time scales (years and centuries).

In this study, the life cycle environmental impact of the disposal of 1 ton of tailings was quantitatively analyzed and compared. The boundary delineation of the LCA system in this study is shown in Figure 3. The objectives of this study were to quantitatively analyze and evaluate the types and consumption of resources and energy in the CSDT and DSDT discharge processes from tailings discharge to tailings storage, assess the full life cycle environmental impacts of different processes, examine the resource and environmental issues involved in existing tailings discharge processes and provide evidence for decision making in TSF design optimization.

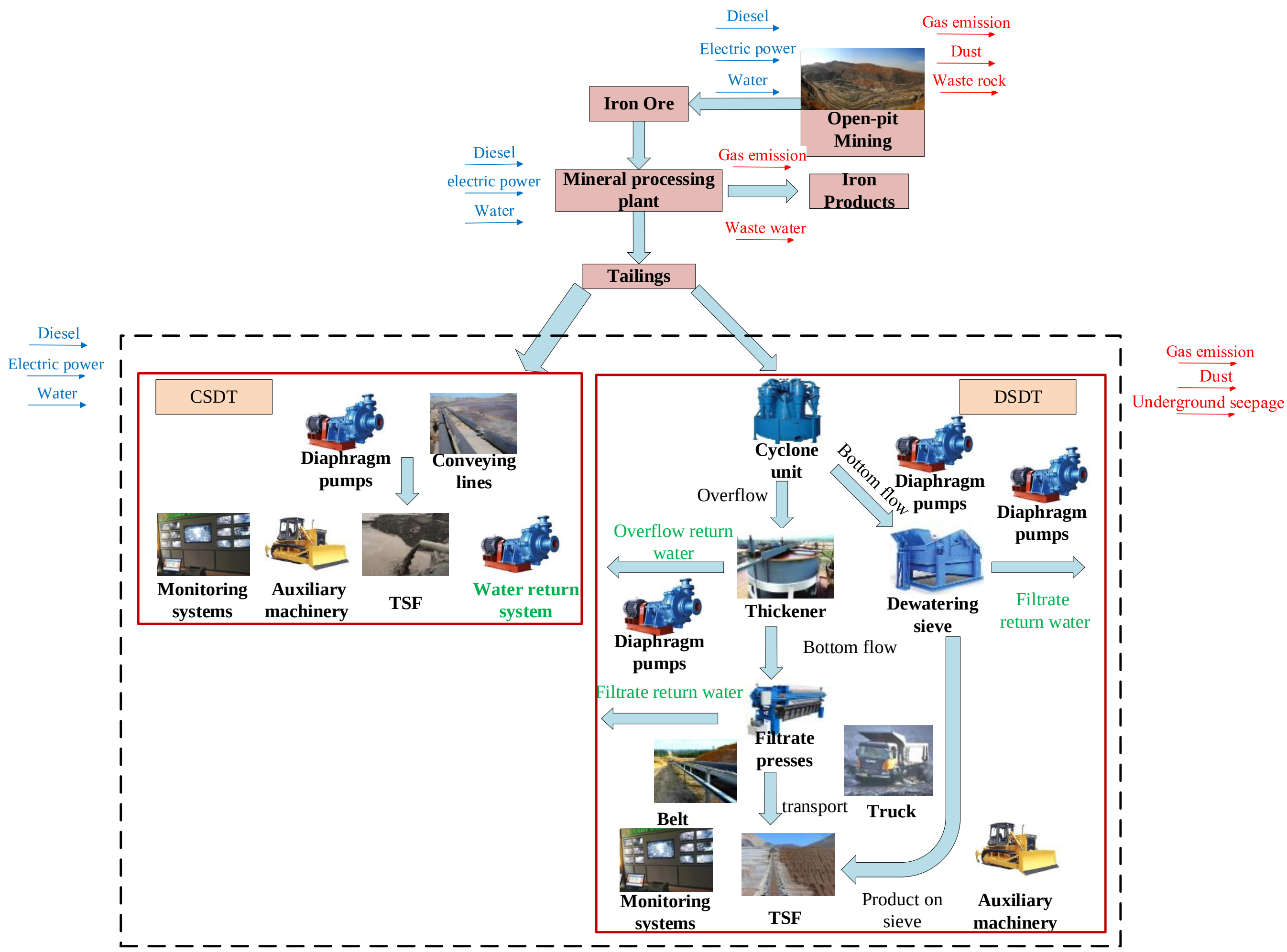

Figure 3. System boundary for cradle-to-gate LCA of the iron mine in northern China.

2.3.3. Data Collection

Data collection and preparation is a key step in LCA. Energy and water consumption data were collected through on-site investigation and design consultation in 2016. The background data needed for the LCA calculation were chosen from regional average data of China in the Ecoinvent 3.4 database. The ReCiPe method was chosen as the evaluation method, which classifies the obtained inventory analysis results into the midpoint indicators of global warming (GW), stratospheric ozone depletion (SOD), ionizing radiation (IR), ozone formation impact on human health (OF–HH), fine particulate matter formation (FPMF), ozone formation impact on terrestrial ecosystems (OF–TE), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HNCT), land use (LU), mineral resource scarcity (MRS), fossil resource scarcity (FRS) and water consumption (WC) [38].

3. Tailings Disposal Process LCA Assessment

3.1. LCA Analysis Scenario Settings

3.1.1. Scenario 1: CSDT Scheme

Under Scenario 1, the low-concentration tailings slurry produced at the processing plant was set as the starting point. The tailings slurry was piped and transported by a slurry pump and directly discharged into the TSF. Clarified water was pumped through a water return system to the water treatment plant for recycling, while the deposited tailings were paved with the assistance of auxiliary machinery. The electrical input for pipeline transport, energy consumption of the auxiliary machinery and water consumption were considered for LCA calculation.

3.1.2. Scenario 2: DSDT by the Belt Conveyor Conveying Scheme

Under Scenario 2, the low-concentration tailings slurry was processed through a complete set of dry discharge treatment equipment, such as cyclone sets, thickeners and dewatering sieves. The tailings slurry was extracted and recycled within the processing plant to produce low-moisture content dry stack tailings. The dry stack tailings were transported to the TSF by a belt conveyor. In the TSF, the tailings stack was spread out and arranged with the assistance of auxiliary machinery. This scenario considered the electrical consumption of the belt conveyor and dry stacking processing and the energy consumption of the auxiliary machinery in the stockpile.

3.1.3. Scenario 3: DSDT by Truck Transport Scheme

Similar to Scenario 2, the low-concentration tailings slurry was processed in the processing plant and produced as low-moisture content dry stack tailings. The stack was then transported to the TSF by truck. Similarly, auxiliary machinery was used to spread the dry stack tailings. The electrical energy consumption of the dry stacking equipment and energy consumption of the trucks and auxiliary machinery were used for comparative analysis.

3.2. LCA Input Data

3.2.1. CSDT Process Data

The average daily processing volume of tailings slurry is 23,000 t. The water consumed by the processing plant for tailings processing and conveying is 908 t/h, including 417.68 t/h of recycled water and 490.32 t/h of fresh water. A total of 3473.84 t/h of tailings and wastewater is discharged into the tailings pond, including 1389.54 t/h of tailings, and two sets of diaphragm pumps with a total power of 1360 kW are installed. The data obtained via on-site investigation are provided in Table 1.

Table 1. CSDT scheme LCA data.

Category	Value	Unit
Water consumption	908.00	t/h
Recycled water consumption	417.68	t/h
Fresh water consumption	490.32	t/h
Volume of the tailings and wastewater discharged	3473.84	t/h
Volume of the tailings discharged	1389.54	t/h
Diesel consumption of the auxiliary machinery at the TSF (per ton of tailings)	13.08	g/t
Slurry pump capacity	680.00	kW

3.2.2. DSDT Process Data

The DSDT scheme was designed according to the case background of 5000 t/d, equipped with two thickeners, each with a motor power of 7.5 kW; six groups of dewatering sieves, each with a power of 14.8 kW; four diaphragm pumps, each with a power of 75 kW; and two groups of cyclones. The total installed power of the tailings dry treatment plant is 403.8 kW. The total power of the belt conveyor is 929 kW/h if belt conveyance is used, based on a linear distance of 2.85 km and a height difference of 115 m. If truck transport is used, the total surface road distance is 6.92 km, and the amount of diesel consumed per ton of tailings transported is 68.41 g. The data used are listed in Table 2.

Table 2. DSDT scheme LCA data.

Category	Value	Number	Unit
Thickener capacity	7.5	2	kW
Dewatering sieve capacity	14.8	6	kW
Slurry pump capacity	75	4	kW
Cyclone set	-	2	-
DSDT equipment total capacity	403.8	-	kW
Belt conveyance distance	2.85	-	km
Total capacity of belt conveyors	929	-	kW
Truck transport distance	6.92	-	km
Diesel consumption of truck transport (per ton of tailings)	68.41	-	g/t
Diesel consumption of the auxiliary machinery at the TSF (per ton of tailings)	10.2	-	g/t

Considering the system boundary shown in Figure 3 and the consumption type difference between the CSDT and DSDT schemes, the data collected were converted into uniform units to calculate statistics on the energy and resource consumption levels per ton of tailings disposed. According to the Renewable Energy Data Book published by the National Energy Administration, the diesel combustion equivalent was chosen as 42.705 MJ/kg. The diesel and electricity consumption units were converted into MJ and kWh, respectively.

4. Results

4.1. Comparative LCA of the Various Tailings Discharge Schemes

The calculated normalized and characterized LCA results are provided in Table 3 and Figure 4, respectively.

Table 3. Normalized LCA results of tailings discharge schemes.

Type of Impact	Unit	Scenario 1	Scenario 2	Scenario 3
GW	kg CO2 eq	1.32	7.96	3.08
SOD	kg CFC11 eq	2.70×10^{-7}	1.40×10^{-6}	7.05×10^{-7}
IR	kBq Co-60 eq	2.01×10^{-2}	1.14×10^{-1}	5.09×10^{-2}
OF, HH	kg NOx eq	3.41×10^{-3}	1.84×10^{-2}	9.43×10^{-3}
FPMF	kg PM2.5 eq	2.20×10^{-3}	1.27×10^{-2}	5.46×10^{-3}
OF, TE	kg NOx eq	3.43×10^{-3}	1.84×10^{-2}	9.52×10^{-3}
TA	kg SO2 eq	5.22×10^{-3}	3.09×10^{-2}	1.24×10^{-2}
FE	kg P eq	2.20×10^{-4}	1.21×10^{-3}	5.50×10^{-4}
ME	kg N eq	5.10×10^{-5}	7.50×10^{-5}	3.51×10^{-5}
TET	kg 1,4-DCB	1.23	6.25	3.64
FET	kg 1,4-DCB	3.64×10^{-2}	2.20×10^{-1}	8.29×10^{-2}
MET	kg 1,4-DCB	4.66×10^{-2}	2.80×10^{-1}	1.08×10^{-1}
HCT	kg 1,4-DCB	3.92×10^{-2}	2.05×10^{-1}	1.09×10^{-1}
HNCT	kg 1,4-DCB	6.27×10^{-1}	2.26	2.40
LU	m2a crop eq	2.04×10^{-2}	8.61×10^{-2}	7.22×10^{-2}
MRD	kg Cu eq	1.68×10^{-3}	4.25×10^{-3}	7.63×10^{-3}
FRS	kg oil eq	2.46×10^{-1}	1.42	6.10×10^{-1}
WC	m3	3.49×10^{-1}	1.16×10^{-2}	6.54×10^{-3}

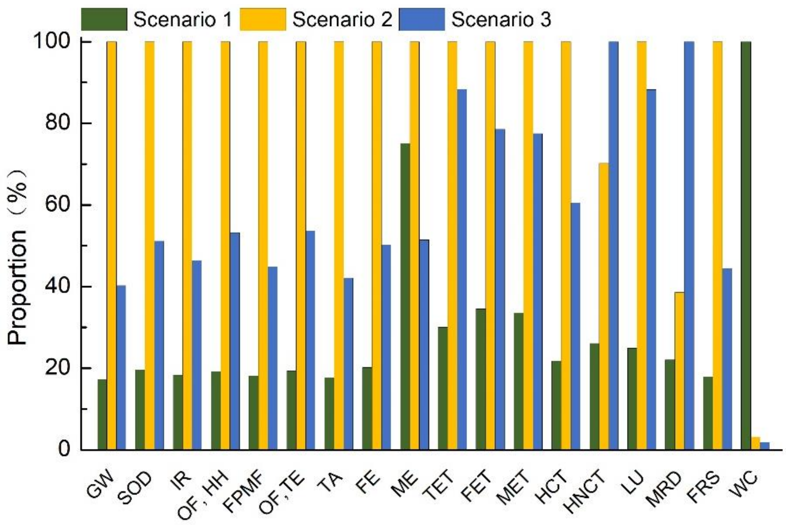

Figure 4. Characterized LCA results for the tailings discharge schemes.

Under Scenario 1 (CSDT scheme), only the WC indicator was higher than that under the DSDT discharge schemes, reaching 30 times higher than that under Scenario 2 and 53 times higher than that under Scenario 3. In water-scarce areas, CSDT could significantly increase the environmental burden. The ME indicator was 32% lower than that under Scenario 2 and 21% higher than that under Scenario 3. The other 16 environmental impact indicators were all lower than those for the DSDT process. The results indicate that the CSDT scheme generated a lower life cycle environmental impact without considering the WC environmental impact indicators.

The Scenario 2 (DSDT by belt conveyance scheme) process was the least environmentally friendly, with its 15 environmental indicators reaching the highest values. Only two environmental impact indicators under Scenario 3 (DSDT by truck transport scheme) were higher than those under Scenario 2. The other 16 environmental impact indicators were significantly lower, indicating that under the DSDT scheme, the environmental benefits of truck transportation were better than those of belt conveyance in the case study.

The normalized and characterized LCA results are presented below, with a detailed analysis of the source components of the environmental impacts and suggestions to improve each process related to the main life cycle environmental impact indicators.

4.2. Scenario 1: CSDT Scheme

Normalized LCA results for the CSDT scheme were obtained, as listed in Table 4 and Figure 5.

Table 4. Normalized LCA results for Scenario 1.

Type of Impact	Unit	Total	Water Consumption	Energy Consumption (Auxiliary Machinery)	Electricity Consumption	Waste Water Discharge
GW	kg CO2 eq	1.32	0	1.16×10^{-1}	1.20	3.95×10^{-3}
SOD	kg CFC11 eq	2.70×10^{-7}	0	4.70×10^{-8}	2.10×10^{-7}	9.40×10^{-9}
IR	kBq Co-60 eq	2.01×10^{-2}	0	2.84×10^{-3}	1.71×10^{-2}	1.60×10^{-4}
OF, HH	kg NOx eq	3.41×10^{-3}	0	6.70×10^{-4}	2.73×10^{-3}	1.30×10^{-5}
FPMF	kg PM2.5 eq	2.20×10^{-3}	0	2.80×10^{-4}	1.91×10^{-3}	9.90×10^{-6}
OF, TE	kg NOx eq	3.43×10^{-3}	0	6.80×10^{-4}	2.74×10^{-3}	1.30×10^{-5}
TA	kg SO2 eq	5.22×10^{-3}	0	5.30×10^{-4}	4.66×10^{-3}	2.70×10^{-5}
FE	kg P eq	2.20×10^{-4}	0	3.10×10^{-5}	1.80×10^{-4}	7.40×10^{-6}
ME	kg N eq	5.10×10^{-5}	0	2.10×10^{-6}	1.10×10^{-5}	3.80×10^{-5}
TET	kg 1,4-DCB	1.23	0	3.02×10^{-1}	9.20×10^{-1}	1.33×10^{-2}
FET	kg 1,4-DCB	3.64×10^{-2}	0	2.80×10^{-3}	3.34×10^{-2}	2.30×10^{-4}
MET	kg 1,4-DCB	4.66×10^{-2}	0	3.95×10^{-3}	4.23×10^{-2}	3.20×10^{-4}
HCT	kg 1,4-DCB	3.92×10^{-2}	0	8.18×10^{-3}	3.04×10^{-2}	6.80×10^{-4}
HNCT	kg 1,4-DCB	6.27×10^{-1}	0	2.98×10^{-1}	3.11×10^{-1}	1.87×10^{-2}
LU	m2a crop eq	2.04×10^{-2}	0	7.99×10^{-3}	1.22×10^{-2}	1.50×10^{-4}
MRD	kg Cu eq	1.68×10^{-3}	0	1.10×10^{-3}	5.20×10^{-4}	6.40×10^{-5}
FRS	kg oil eq	2.46×10^{-1}	0	3.11×10^{-2}	2.14×10^{-1}	8.40×10^{-4}
WC	m3	3.49×10^{-1}	3.53×10^{-1}	5.20×10^{-4}	1.71×10^{-3}	-5.80×10^{-3}

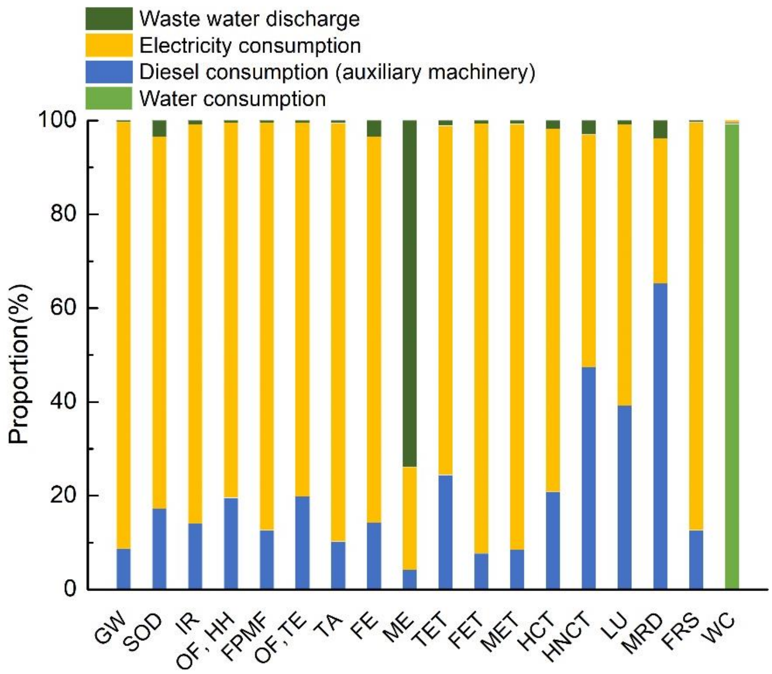

Figure 5. Normalized LCA results for Scenario 1.

The wastewater discharge under the CSDT scheme accounted for the highest proportion of ME, at 73.88% (3.8×10^{-5} kg N equivalent). The wastewater environmental impact of CSDT should receive sufficient attention. Moreover, the CSDT scheme consumed a large amount of recycled water and fresh water. The results indicate that 0.35286 m^3 of freshwater was consumed per ton of tailings disposed of. In certain areas with scarce water resources, the feasibility of the CSDT scheme should be carefully considered.

The environmental impact of electricity consumption while conveying tailings dominated the 15 life cycle environmental impact indicators, such as 90.94% of GW, 79.26% of SOD and 86.86% of FPMF. This indicates that the environmental impact could be mainly attributed to the consumption of electric energy due to the long distance of pipeline transportation and the high lift caused by the terrain elevation differences. According to National Energy Administration statistics, China's current electricity structure is still dominated by coal power, which accounted for 75.08% of the total electricity generation in the first quarter of 2018, followed by hydropower (13.15%), wind power (6.1%) and nuclear power (4.17%). The high-power-consumption pipeline conveying system is the main source of the CSDT scheme environmental impact.

The key measures for improving the CSDT LCA environmental impacts include increasing the tailings slurry concentration, reducing water consumption, optimizing TSF site planning, and minimizing the distance and height difference of the pipeline to reduce the power consumption of the conveying system.

4.3. Scenario 2: DSDT by Belt conveyance Scheme

Normalized LCA results for Scenario 2 (DSDT by belt conveyance scheme) were obtained and are listed in Table 5 and Figure 6.

Table 5. Normalized LCA results for Scenario 2.

Type of Impact	Unit	Total	Energy Consumption (Auxiliary Machinery)	Electricity Consumption (Dry Stacking Processing)	Electricity Consumption (Belt Conveyance)
GW	kg CO2 eq	7.67	9.06×10^{-2}	2.39	5.49
SOD	kg CFC11 eq	1.38×10^{-6}	3.64×10^{-8}	4.24×10^{-7}	9.80×10^{-7}
IR	kBq Co-60 eq	1.10×10^{-1}	2.22×10^{-3}	3.38×10^{-2}	7.78×10^{-2}
OF, HH	kg NOx eq	1.77×10^{-2}	5.20×10^{-4}	5.41×10^{-3}	1.25×10^{-2}
FPMF	kg PM2.5 eq	1.22×10^{-2}	2.20×10^{-4}	3.78×10^{-3}	8.70×10^{-3}
OF, TE	kg NOx eq	1.78×10^{-2}	5.30×10^{-4}	5.42×10^{-3}	1.25×10^{-2}
TA	kg SO2 eq	2.95×10^{-2}	4.20×10^{-4}	9.23×10^{-3}	2.12×10^{-2}
FE	kg P eq	1.09×10^{-3}	2.45×10^{-5}	3.60×10^{-4}	8.20×10^{-4}
ME	kg N eq	6.83×10^{-5}	1.67×10^{-6}	2.23×10^{-5}	5.10×10^{-5}
TET	kg 1,4-DCB	4.12	2.35×10^{-1}	1.82	4.19
FET	kg 1,4-DCB	1.06×10^{-1}	2.18×10^{-3}	6.61×10^{-2}	1.52×10^{-1}
MET	kg 1,4-DCB	1.39×10^{-1}	3.08×10^{-3}	8.38×10^{-2}	1.93×10^{-1}
HCT	kg 1,4-DCB	1.81×10^{-1}	6.38×10^{-3}	6.02×10^{-2}	1.38×10^{-1}
HNCT	kg 1,4-DCB	1.69	2.32×10^{-1}	6.15×10^{-1}	1.41
LU	m2a crop eq	8.18×10^{-2}	6.23×10^{-3}	2.42×10^{-2}	5.57×10^{-2}
MRD	kg Cu eq	2.94×10^{-3}	8.60×10^{-4}	1.03×10^{-3}	2.37×10^{-3}
FRS	kg oil eq	1.37	2.42×10^{-2}	4.23×10^{-1}	9.73×10^{-1}
WC	m3	1.10×10^{-2}	4.10×10^{-4}	3.39×10^{-3}	7.81×10^{-3}

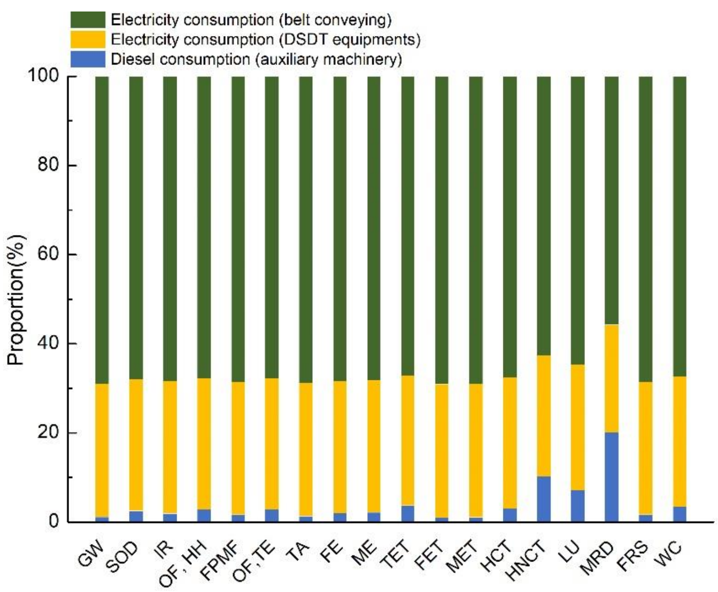

Figure 6. Normalized LCA results for Scenario 2.

Belt conveyance under Scenario 2 dominated the LCA environmental impact and accounted for the highest proportion of the 16 environmental indicators, e.g., 68.9% of GW, 67.93% of SOD, 68.50 of FPMF and 68.51% of FRS. The environmental impact caused by the power consumption of dry stack processing equipment, such as thickeners, filter presses and dewatering sieves, was also not negligible, accounting for more than 24% of all environmental impact indicators. Auxiliary machinery exerted a slight impact on all lifecycle indicators. This indicates that the LCA environmental impact of Scenario 2 was mainly due to the transportation process. The linear distance from the processing plant to the TSF is 2.85 km, and the height difference is 115 m. This scheme is expected to provide better environmental benefits if the TSF site can be located within a reasonable distance.

4.4. Scenario 3: DSDT by Truck Transport Scheme

Normalized LCA results for Scenario 3 (DSDT by truck transport scheme) were obtained, as summarized in Table 6 and Figure 7.

Table 6. Normalized LCA results for Scenario 3.

Type of Impact	Unit	Total	Energy Consumption (Auxiliary Machinery)	Electricity Consumption (Dry Stacking Equipment)	Energy Consumption (Trucks)
GW	kg CO2 eq	3.08	9.06×10^{-2}	2.39	6.07×10^{-1}
SOD	kg CFC11 eq	7.05×10^{-7}	3.64×10^{-8}	4.24×10^{-7}	2.44×10^{-7}
IR	kBq Co-60 eq	5.09×10^{-2}	2.22×10^{-3}	3.38×10^{-2}	1.49×10^{-2}
OF, HH	kg NOx eq	9.43×10^{-3}	5.20×10^{-4}	5.41×10^{-3}	3.49×10^{-3}
FPMF	kg PM2.5 eq	5.46×10^{-3}	2.20×10^{-4}	3.78×10^{-3}	1.46×10^{-3}
OF, TE	kg NOx eq	9.52×10^{-3}	5.30×10^{-4}	5.42×10^{-3}	3.57×10^{-3}
TA	kg SO2 eq	1.24×10^{-2}	4.20×10^{-4}	9.23×10^{-3}	2.79×10^{-3}
FE	kg P eq	5.50×10^{-4}	2.45×10^{-5}	3.60×10^{-4}	1.60×10^{-4}
ME	kg N eq	3.51×10^{-5}	1.67×10^{-6}	2.23×10^{-5}	1.12×10^{-5}
TET	kg 1,4-DCB	3.64	2.35×10^{-1}	1.82	1.58
FET	kg 1,4-DCB	8.29×10^{-2}	2.18×10^{-3}	6.61×10^{-2}	1.46×10^{-2}
MET	kg 1,4-DCB	1.08×10^{-1}	3.08×10^{-3}	8.38×10^{-2}	2.07×10^{-2}
HCT	kg 1,4-DCB	1.09×10^{-1}	6.38×10^{-3}	6.02×10^{-2}	4.28×10^{-2}
HNCT	kg 1,4-DCB	2.40	2.32×10^{-1}	6.15×10^{-1}	1.56
LU	m2a crop eq	7.22×10^{-2}	6.23×10^{-3}	2.42×10^{-2}	4.18×10^{-2}
MRD	kg Cu eq	7.63×10^{-3}	8.60×10^{-4}	1.03×10^{-3}	5.75×10^{-3}
FRS	kg oil eq	6.10×10^{-1}	2.42×10^{-2}	4.23×10^{-1}	1.63×10^{-1}
WC	m3	6.54×10^{-3}	4.10×10^{-4}	3.39×10^{-3}	2.74×10^{-3}

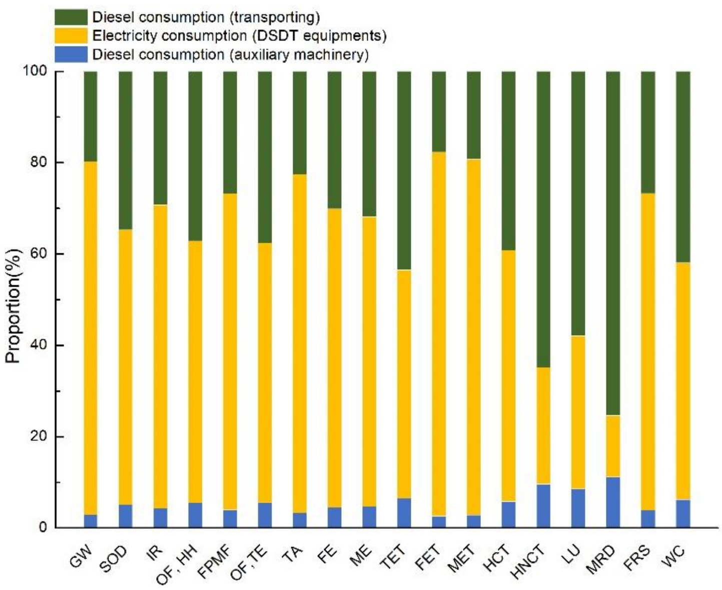

Figure 7. Normalized LCA results for Scenario 3.

Only three environmental impact indicators of tailings transport-related diesel consumption under Scenario 3 dominated, including HNCT, LU and MRS, while the remaining 15 indicators were significantly lower. This indicates that the truck transport scheme was more suitable for long-distance tailings transport than the belt conveyance scheme. Similarly, the environmental impact of ancillary machinery diesel consumption was also relatively limited. However, the DSDT equipment electricity consumption dominated 15 environmental impact indicators, including GW, SOD, IR, OF, HH, FPMF, OF, TE, TA, FE, ME, TET, FET, MET, HCT, FRS and WC, each with a proportion over 50%. This suggests that the LCA environmental impact of this scheme could be mainly attributed to the DSDT equipment. Simplifying the DSDT process and improving the equipment efficiency could constitute the main direction to achieve a more sustainable tailings disposal scheme.

5. Discussion

Based on the system boundary delineated in this study, the environmental impact indicators of the CSDT scheme were significantly lower than those of the DSDT schemes, without considering tailings disposal water consumption. This mainly occurred because the DSDT schemes consumed more fossil energy or electricity energy than the CSDT scheme. The water resources were sufficient in the case study research area. Therefore, considering the LCA system boundary delineated in the case study, the CSDT scheme was still more environmentally friendly and sustainable.

However, the engineering background, especially TSF capacity and safety, should be further considered in the decision-making process. The advantages and disadvantages of the DSDT schemes, input data quality, and decision making using LCA results will be discussed in this section.

5.1. Advantages and Disadvantages of the DSDT Schemes

5.1.1. Advantages of the DSDT Schemes

(1) Better slope stability and higher tailings discharge piling angle

CSDT technology usually uses coarse-grained tailings to build the dam body, especially with the upstream damming method, which exhibits poor stability and can easily liquefy under seismic conditions [39]. In contrast, DSDT technology can avoid dam phreatic seepage damage problems. The high tailings discharge piling angle will not cause catastrophic accidents, as extensive transport of dry stack tailings can be stored within the TSF [20,24,40]. Thus, this scheme is suitable for areas with frequent seismic activity.

Tailings dam breach disasters can yield serious consequences in terms of human casualties, environmental pollution, social impact, mining company operation and even industrial development [13]. Typical examples are the two tailings dam failures in Brazil in 2015 and 2019 [10,11], where companies faced very high fines, environmental clean-up burdens, adverse social impacts, and tightened government control policies, resulting in incalculable short- and long-term losses. In particular, for the 1425 "overhead TSFs" in China [3], which are significant potential hazardous TSFs located upstream and within only 1 km of residential areas, industrial plants, schools, hospitals and other important facilities, the advantages of a greater slope stability and less notable consequences of potential dam breaches under DSDT schemes are critical for the disaster prevention and mitigation.

In addition, the mandatory standards of TSF safety monitoring indicators under the DSDT scheme are generally lower than those under the traditional CSDT scheme. The standards state that at least 10 indicators should be monitored for CSDT TSFs, including surface and internal displacements, external slope ratio, phreatic line, and beach length. In contrast, only four indicators should be monitored for DSDT TSFs, including surface displacement and external slope ratio. Therefore, DSDT schemes could effectively reduce the construction and maintenance costs of safety monitoring systems.

(2) Disposal of low-water-content tailings

The water consumption of mineral processing plants and tailings disposal can be significantly reduced by applying the DSDT scheme and recycling water during dry stack processing of wet tailings. This scheme is considered to provide satisfactory environmental and economic benefits, especially in water-scarce areas [21]. Moreover, the transport methods of low-water-content tailings stacks can overcome the problems of the pipeline freezing and clogging during the transport of slurry tailings, making the DSDT scheme suitable for tailings discharge in alpine regions. In addition, the permeability of dry stack tailings is low, effectively reducing groundwater or soil system pollution due to acidification of water bodies or seepage of toxic and harmful substances such as heavy metals.

(3) Smaller footprint and higher capacity

The TSF capacity remains an essential prerequisite to ensure continuous mining activities for most mines. In China, the examination and approval of TSF storage capacity expansion are becoming increasingly strict, as increasing attention has been given to the supervision of environmental protection and safety mining production. Moreover, this scheme contributes to landscape protection and is suitable for mine sites where the topography is not suitable for tailings dam construction. Therefore, the DSDT scheme, with a smaller footprint and higher capacity, is more attractive for newly planned TSFs.

5.1.2. Disadvantages of the DSDT Scheme

(1) High initial investment

The DSDT scheme requires the purchase of a complete set of tailings disposal equipment, such as thickeners, filter presses, and dewatering sieves, during the early stages of TSF site construction. This high initial investment can greatly increase the economic burden and dominate the decision-making process of mining companies.

(2) Low tailings processing efficiency

Large-scale tailings discharge is difficult, because DSDT equipment provides a limited processing capacity, and belt conveyance or truck transport methods are less efficient than the traditional CSDT pipeline transport method. Improving the dewatering efficiency of the equipment, simplifying the process, and reducing costs are crucial to future applications of this technology.

(3) High climatic requirements

Under current technical conditions, DSDT is limited by regional precipitation. In rainy climate regions, flood discharge and leakage pollution control of DSDT TSFs have become major bottlenecks in the implementation of this technology [41,42].

(4) Dust pollution

In contrast to CSDT TSFs, where wet tailings are mostly stored under water surface coverage, dry stack tailings may cause dust pollution, especially in dry and windy areas. This may lead to serious air pollution, respiratory diseases, and occupational health problems for workers [43].

5.2. Quality of the LCA Input Data

High-quality data are a decisive factor in generating reliable LCA results There are problems and difficulties in the acquisition, evaluation, maintenance, and updating of LCA data. In the mining industry, LCA is still a new interdisciplinary approach. It is difficult to summarize universal calculation methods due to the complexity of mineral resource extraction process and the large number of environmental pollution indicators involved. Mining and mineral processing steps vary depending on the mine production conditions. Four main reasons for the difficulty of obtaining LCA data are listed below:

(1) Poor cooperation of mining companies

The process flow, raw materials and energy inputs involved in LCA calculations are often sensitive data for mining companies. Most companies exhibit a notable tendency to keep these data confidential. Some mining companies refuse to disclose data due to the concern that this might lead to malicious competition, regulatory penalties, or public panic. The environmental aspects of mine production and pollutant discharge processes therefore remain unclear, such as tailings disposal.

(2) Complexity of data collection

LCA data collection and measurement often require professional theoretical knowledge and a substantial amount of meticulous work. Most mining companies possess limited knowledge to collect high-quality data, especially small mining companies. The accuracy and credibility of the collected data are thus difficult to guarantee.

(3) Data timeliness

As the mine production conditions and process vary under different deposit conditions or mining developing stages, LCA data also vary. For example, the energy consumption and emissions of mining trucks vary with different loads, working conditions and even operating habits, making it more difficult to obtain high-quality data.

(4) Diversity of data sources

The quality of data sources such as databases, literature data, unpublished data and field measurement and calculation data is uneven, and it is difficult to summarize, integrate and maintain these data. Moreover, most mainstream LCA databases pertain to Europe and the United States, which may not conform to China's national conditions, and the data are difficult to directly substitute.

In addition, due to the complexity of the system and the lack of data, differences in TSF dust emissions and underground water seepage were ignored in this study. Equipment manufacturing and maintenance aspects were also not included in the system boundary.

5.3. Application of the LCA Results in The Case Study

DSDT schemes are deemed to be a more advanced technology with higher performance with respect to slope stability, seismic resistance, storage capacity usage and waste water recycling, shorter closure and reclamation cycles [44]. Based on the fact that the remaining capacity of the TSF was only 10.9 million m^3, which could only be used for 3.68 years with continuation of the CSDT scheme, the DSDT scheme was then preferable, considering its smaller capacity usage. According to the on-site data, the capacity occupancy rate decreased by 70% following the transformation of the tailings disposal scheme. Meanwhile, the TSF site in this case study was a highly threatening TSF located upstream and within only 0.8 km of downstream residential communities. The CSDT scheme was thus excluded due to its poorer slope stability, higher dam breach rate and greater potential accident consequences.

On the other hand, the LCA results were vital in decision-making with respect to transport methods in the DSDT scheme. The TSF was located 2.85 km away from the mineral processing plant, with a height difference of 115 m. The LCA environmental performance of the DSDT scheme by truck transport was significantly better than that of the DSDT scheme by belt conveyance.

Therefore, by comprehensively considering the severe consequences of potential tailings dam breach accidents, the low TSF remaining capacity and environmental, social and policy uncertainties associated with the traditional CSDT scheme, the DSDT scheme by truck transport was eventually preferred and implemented.

6. Conclusions

Based on a case study of an open-pit iron mine in northern China, this study adopted the life cycle assessment (LCA) method to compare the environmental impacts of three tailings disposal schemes of conventional slurry disposal technology (CSDT), dry stack disposal technology (DSDT) by belt conveyance and DSDT by truck transport. The system boundary was defined from the output of low-concentration tailings slurry disposal of the processing plant to the input into tailings storage facilities (TSFs). The LCA environmental impacts were then calculated. The main conclusions were as follows:

(1) Ignoring the environmental impact of water consumption, the CSDT scheme yielded a lower life cycle environmental impact. Reducing the water consumption of the process, increasing the concentration of the tailings slurry, shortening the distance of pipeline transport, and reasonably disposing of seepage wastewater at the TSF should

be the main aspects considered in order to improve the CSDT process and reduce the associated life cycle environmental impact.

(2) The LCA environmental impacts of the DSDT scheme by belt conveyance were mainly due to the transport component, which requires more rational site planning of the TSF. The environmental impact of the DSDT scheme by trucking transport mainly stemmed from the energy consumption of DSDT equipment. Simplifying the process and improving the equipment efficiency are the focusing components to enhance the environmental benefits of this scheme.

(3) DSDT exhibits a smaller footprint, better slope stability, notable conduciveness to water resource conservation and shorter site closure and reclamation cycles and could provide better environmental and economic benefits in specific areas such as alpine, arid, high-seismic intensity, complex terrain, and ecologically fragile areas, or TSFs with high dam breach-related risks. The construction and maintenance costs of TSF safety monitoring systems are relatively low. However, the required investment in DSDT equipment is high, and the climatic conditions are exacting.

(4) The DSDT scheme by truck transport was eventually preferred in the case study based on the LCA results and concerns regarding TSF safety, the environment and remaining capacity. It is thus recommended that the LCA of environmental impacts be considered in the decision-making process for sustainable tailings disposal design.

Author Contributions: Conceptualization, methodology, software and funding acquisition, K.W.; investigation, X.Y. and C.Y.; writing—original draft preparation, K.W. and Z.Z.; visualization, L.Z. writing—review and editing, K.W. and M.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Natural Science Foundation of China (grant number 52104138), Shandong Provincial Natural Science Foundation (grant number ZR2020QE101) and Postdoctoral Applied Research Project Foundation of Qingdao.

Data Availability Statement: Data are contained within the article.

Acknowledgments: We acknowledge the mine site for providing the energy consumption data.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Hudson-Edwards, K. Tackling mine wastes. *Science* **2016**, *352*, 288–290. [CrossRef] [PubMed]
2. Adiansyah, J.S.; Rosano, M.; Vink, S.; Keir, G. A framework for a sustainable approach to mine tailings management: Disposal strategies. *J. Clean. Prod.* **2015**, *108*, 1050–1062. [CrossRef]
3. Li, W.; Wang, H.; Wang, X.; Zhu, X. *The Report of Mineral Resources Saving and Comprehensive Utilization in China (2021)*; Geological Publishing House: Beijing, China, 2020.
4. Aiai, W.; Shuai, C.; Erol, Y. Influence of types and contents of nano cellulose materials as reinforcement on stability performance of cementitious tailings backfill. *Constr. Build. Mater.* **2020**, *344*, 128179. [CrossRef]
5. Huan, Z.; Shuai, C.; Erol, Y. Influence of 3D-printed polymer structures on dynamic splitting and crack propagation behavior of cementitious tailings backfill. *Constr. Build. Mater.* **2022**, *343*, 128137. [CrossRef]
6. Zhao, Z.; Cao, S.; Yilmaz, E. Effect of layer thickness on flexural property and microstructure of 3D printed rhomboid polymer reinforced cemented tailings composites. *Int. J. Miner. Metall. Mater.* **2022**, *30*, 1–14. [CrossRef]
7. Wang, K.; Yang, P.; Yu, G.; Yang, C.; Zhu, L. 3D Numerical Modelling of Tailings Dam Breach Run Out Flow over Complex Terrain: A Multidisciplinary Procedure. *Water* **2020**, *12*, 2538. [CrossRef]
8. Li, Q.M.; Yuan, H.N.; Zhong, M.H. Safety assessment of waste rock dump built on existing tailings ponds. *J. Cent. South Univ.* **2015**, *22*, 2707–2718. [CrossRef]
9. Chen, C.C. Hazards identification and characterisation of the tailings storage facility dam failure and engineering applications. *Int. J. Min. Reclam. Environ.* **2022**, *36*, 399–418. [CrossRef]
10. WISE Uranium Project. Chronology of Major Tailings Dam Failures (from 1960). Available online: https://www.wise-uranium.org/mdaf.html (accessed on 20 August 2021).
11. Burritt, R.L.; Christ, K.L. Water risk in mining: Analysis of the Samarco dam failure. *J. Clean. Prod.* **2018**, *178*, 196–205. [CrossRef]
12. Cheng, D.; Cui, Y.; Li, Z.; Iqbal, J. Watch Out for the Tailings Pond, a Sharp Edge Hanging over Our Heads: Lessons Learned and Perceptions from the Brumadinho Tailings Dam Failure Disaster. *Remote Sens.* **2021**, *13*, 1775. [CrossRef]

13. Hamade, T.; Mitri, H. Reliability-based approach to the geotechnical design of tailings dams. *Int. J. Min. Reclam. Environ.* **2013**, *27*, 377–392. [CrossRef]
14. Hu, S.H.; Chen, Y.F.; Liu, W.; Zhou, S.; Hu, R. Effect of seepage control on stability of a tailings dam during its staged construction with a stepwise-coupled hydro-mechanical model. *Int. J. Min. Reclam. Environ.* **2015**, *29*, 125–140. [CrossRef]
15. Jiao, H.; Wang, S.; Yang, Y.; Chen, X. Water recovery improvement by shearing of gravity-thickened tailings for cemented paste backfill. *J. Clean. Prod.* **2020**, *245*. [CrossRef]
16. Edraki, M.; Baumgartl, T.; Manlapig, E.; Bradshaw, D.; Franks, D.M.; Moran, C.J. Designing mine tailings for better environmental, social and economic outcomes: A review of alternative approaches. *J. Clean. Prod.* **2014**, *84*, 411–420. [CrossRef]
17. Yilmaz, E.; Benzaazoua, M.; Bussiere, B.; Pouliot, S. Influence of disposal configurations on hydrogeological behaviour of sulphidic paste tailings: A field experimental study. *Int. J. Miner. Processing* **2014**, *131*, 12–25. [CrossRef]
18. Ruan, Z.E.; Li, C.P.; Shi, C. Numerical simulation of flocculation and settling behavior of whole-tailings particles in deep-cone thickener. *J. Cent. South Univ.* **2016**, *23*, 740–749. [CrossRef]
19. Deschamps, T.; Benzaazoua, M.; Bussiere, B.; Aubertin, M. Laboratory study of surface paste disposal for sulfidic tailings: Physical model testing. *Miner. Eng.* **2011**, *24*, 794–806. [CrossRef]
20. Li, S.; Chen, Q.S.; Wang, X.M. Superiority of Filtered Tailings Storage Facility to Conventional Tailings Impoundment in Southern Rainy Regions of China. *Sustainability* **2016**, *8*, 1130. [CrossRef]
21. Vargas, C.C.; Campomanes, G.P. Practical Experience of Filtered Tailings Technology in Chile and Peru: An Environmentally Friendly Solution. *Minerals* **2022**, *12*, 889. [CrossRef]
22. Azam, S.; Li, Q. Tailings dam failures: A review of the last one hundred years. *Geotech. News* **2010**, *28*, 50–54.
23. Kheirkhah Gildeh, H.; Halliday, A.; Arenas, A.; Zhang, H. Tailings Dam Breach Analysis: A Review of Methods, Practices, and Uncertainties. *Mine Water Environ.* **2020**, *40*, 128–150. [CrossRef]
24. Gomes, R.B.; De Tomi, G.; Assis, P.S. Iron ore tailings dry stacking in Pau Branco mine, Brazil. *J. Mater. Res. Technol.* **2016**, *5*, 339–344. [CrossRef]
25. Oldecop, L.A.; Rodari, G.J. Unsaturated mine tailings disposal. *Soils Rocks* **2021**, *44*, e2021067421. [CrossRef]
26. Finnveden, G.; Hauschild, M.Z.; Ekvall, T.; Guinée, J.; Heijungs, R.; Hellweg, S.; Koehler, A.; Pennington, D.; Suh, S. Recent developments in Life Cycle Assessment. *J. Environ. Manag.* **2009**, *91*, 1–21. [CrossRef] [PubMed]
27. Hauschild, M.Z.; Rosenbaum, R.K.; Olsen, S.I. *Life Cycle Assessment*; Springer: Berlin/Heidelberg, Germany, 2018.
28. Yi, Q.P.; Tang, C.P. Environmental impact assessment of magnesium alloy automobile hub based on life cycle assessment. *J. Cent. South Univ.* **2018**, *25*, 1870–1878. [CrossRef]
29. Liu, C.R.; Tang, Y.F.; Wang, H.Q.; Liu, Z.Q.; Yang, S.; Li, C.J.; Jin, W.T. Comparison of life cycle performance of distributed energy system and conventional energy system for district heating and cooling in China. *J. Cent. South Univ.* **2022**, *29*, 2357–2376. [CrossRef]
30. Yu, S.; Tao, J. *Product Life Cycle Design and Evaluation*; Science Press: Beijing, China, 2012; p. 250.
31. Segura-Salazar, J.; Lima, F.M.; Tavares, L.M. Life Cycle Assessment in the minerals industry: Current practice, harmonization efforts, and potential improvement through the integration with process simulation. *J. Clean. Prod.* **2019**, *232*, 174–192. [CrossRef]
32. Farjana, S.H.; Huda, N.; Mahmud, M.A.P.; Saidur, R. A review on the impact of mining and mineral processing industries through life cycle assessment. *J. Clean. Prod.* **2019**, *231*, 1200–1217. [CrossRef]
33. Yellishetty, M.; Mudd, G.M.; Shukla, R. Prediction of soil erosion from waste dumps of opencast mines and evaluation of their impacts on the environment. *Int. J. Min. Reclam. Environ.* **2013**, *27*, 88–102. [CrossRef]
34. Song, X.; Pettersen, J.B.; Pedersen, K.B.; Roberg, S. Comparative life cycle assessment of tailings management and energy scenarios for a copper ore mine: A case study in Northern Norway. *J. Clean. Prod.* **2017**, *164*, 892–904. [CrossRef]
35. Tao, M.; Zhang, X.; Wang, S.; Cao, W.; Jiang, Y. Life cycle assessment on lead-zinc ore mining and beneficiation in China. *J. Clean. Prod.* **2019**, *237*. [CrossRef]
36. Beylot, A.; Villeneuve, J. Accounting for the environmental impacts of sulfidic tailings storage in the Life Cycle Assessment of copper production: A case study. *J. Clean. Prod.* **2017**, *153*, 139–145. [CrossRef]
37. Kossoff, D.; Dubbin, W.E.; Alfredsson, M.; Edwards, S.J.; Macklin, M.G.; Hudson-Edwards, K.A. Mine tailings dams: Characteristics, failure, environmental impacts, and remediation. *Appl. Geochem.* **2014**, *51*, 229–245. [CrossRef]
38. Xiao, H.; Yang, D. Environmental impact assessment method based on product life cycle and its application. *Urban Environ. Stud.* **2018**, 88–105.
39. Zhang, C.; Liu, H.M.; Yang, C.H.; Wu, S.W. Mechanical characteristics of non-saturated tailings and dam stability. *Int. J. Min. Reclam. Environ.* **2017**, *31*, 530–543. [CrossRef]
40. Consoli, N.C.; Vogt, J.C.; Silva, J.P.S.; Chaves, H.M.; Scheuermann Filho, H.C.; Moreira, E.B.; Lotero, A. Behaviour of Compacted Filtered Iron Ore Tailings-Portland Cement Blends: New Brazilian Trend for Tailings Disposal by Stacking. *Appl. Sci.-Basel* **2022**, *12*, 836. [CrossRef]
41. Liu, Q.; Liu, D.; Liu, X.; Gao, F.; Li, S. Research and application of surface paste disposal for clay-sized tailings in tropical rainy climate. *Int. J. Miner. Processing* **2016**, *157*, 227–235. [CrossRef]
42. Sracek, O.; Kříbek, B.; Mihaljevič, M.; Ettler, V.; Vaněk, A.; Penížek, V.; Veselovský, F.; Bagai, Z.; Kapusta, J.; Sulovský, P. Mobility of Mn and other trace elements in Mn-rich mine tailings and adjacent creek at Kanye, southeast Botswana. *J. Geochem. Explor.* **2021**, *220*. [CrossRef]

43. Kříbek, B.; Majer, V.; Pašava, J.; Kamona, F.; Mapani, B.; Keder, J.; Ettler, V. Contamination of soils with dust fallout from the tailings dam at the Rosh Pinah area, Namibia: Regional assessment, dust dispersion modeling and environmental consequences. *J. Geochem. Explor.* **2014**, *144*, 391–408. [CrossRef]
44. Bascetin, A.; Tuylu, S. Application of Pb-Zn tailings for surface paste disposal: Geotechnical and geochemical observations. *Int. J. Min. Reclam. Environ.* **2018**, *32*, 312–326. [CrossRef]