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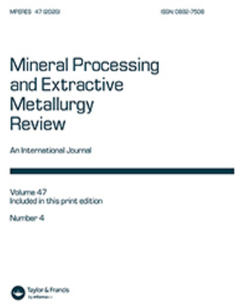
Citation for the original published paper (version of record):
Ramesh, V., Bhadani, K., Asbjörnsson, G. et al (2026). Sustainability Assessment of Celestine Production and Tailings Enrichment with Flexible Circuits. Mineral Processing and Extractive Metallurgy Review, 47(4): 551-571. http://dx.doi.org/10.1080/08827508.2025.2529826



Mineral Processing and Extractive Metallurgy Review
An International Journal

ISSN: 0882-7508 (Print) 1547-7401 (Online) Journal homepage: www.tandfonline.com/journals/gmpr20

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To cite this article: Varun Gowda, Kanishk Bhadani, Gauti Asbjörnsson, Francisco Ortega, Noemi Ariza-Rodríguez, Diego Mesa, Pablo R. Brito-Parada & Magnus Evertsson (2026) Sustainability Assessment of Celestine Production and Tailings Enrichment with Flexible Circuits, Mineral Processing and Extractive Metallurgy Review, 47:4, 551-571, DOI: 10.1080/08827508.2025.2529826

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MINERAL PROCESSING AND EXTRACTIVE METALLURGY REVIEW
2026, VOL. 47, NO. 4, 551–571
https://doi.org/10.1080/08827508.2025.2529826

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Sustainability Assessment of Celestine Production and Tailings Enrichment with Flexible Circuits

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ABSTRACT
Strontium is classified as a critical raw material by the European Commission and is mainly found in celestine ore. Within Europe, largest reserve of celestine is found at a mine in Spain. The mine utilizes diesel-powered mobile machines in the processing circuit, which enable changes in the processing circuit, providing flexibility to handle varying grades of Run-of-Mine ore and produce multiple-size fractions of celestine. However, this flexibility leads to material and energy consumption variations, increasing the complexity of assessing the environmental impacts of celestine. This study investigates the environmental impacts of producing multiple grades and size fractions of celestine in a flexible processing circuit setup, along with economic implications. Using Life Cycle Assessment (LCA), an automatic allocation tool, and site-specific data, the relationship between circuits and the environmental impacts of celestine was investigated. Multiple scenarios were assessed, comprising a mobile crushing plant and additional tailings enrichment in the circuit. Cradle-to-gate LCA results show that, circuit comprising a mobile crushing plant producing multiple-size fractions of celestine had a Global Warming Potential (GWP)-total impact of 1.29 kgCO$_2$-eq./tonne, which is 3% lower than the circuit producing a single size-fraction (1.33 kgCO$_2$-eq./tonne). Circuit with tailing enrichment demonstrated an increased revenue of at least 14% but raised GWP-total by 63%, reaching 2.18 kgCO$_2$-eq./tonne, compared to 1.33 kgCO$_2$-eq./tonne for circuit without enrichment. The increase in GWP-total was mostly attributed to increased consumption of ferrosilicon and diesel during the enrichment process. However, these results are specific to the system boundary assessed in the study. Using revenue calculation and LCA for circuit evaluation helps in comparing economic and environmental aspects of the circuits.

KEYWORDS
Celestine; life cycle assessment (LCA); flexible processing circuit; allocation; tailings enrichment

Introduction

The global demand for raw materials is projected to increase from 79 billion tonnes to 167 billion tonnes by 2060 (European Commission 2023). The latest report on the Critical Raw Materials (CRMs) for the European Union (EU) identifies 32 raw materials as critical. Among these, strontium is classified as a CRM due to its economic importance (EI) and supply risk (SR), rated at 2.6 and 6.5, respectively (European Commission 2023). Strontium primarily occurs in minerals such as celestine (strontium sulfate), strontianite (strontium carbonate), and strontium fluoride, with celestine being the most abundant and significant source (Mesa et al. 2025). Notably, Spain supplies 99% of the EU's strontium, with the Montevive mine hosting the largest celestine reserves in the region (Ariza-Rodríguez et al. 2022).

Due to the decreasing grade of the existing strontium-bearing ores, several production requirements have arisen to satisfy the demand. These requirements include increasing the capacity by expanding the processing capabilities through modification in the processing circuit, as well as including additional processing steps such as the tailings enrichment process. This can lead to an increase in the recovery of celestine. For instance, Ariza-Rodríguez et al. (2022) demonstrated that the tailings (low-grade celestine minerals of about 60% celestine) produced in the crushing and size classification processes can be enriched through grinding and fine-size classification processes based on density to recover valuable celestine.

Generally, any changes in the production process can result in different environmental impacts due to an increase or decrease in the consumption of resources (i.e. material and energy) and waste generation (hazardous and non-hazardous waste). Various environmental assessment methods exist that can be used to quantify the environmental impact. The most notable ones are the Environmental Management System (EMS), Environmental Impact Assessment (EIA), and Life Cycle Assessment (LCA). EMS assesses an organization's operations regarding their effect on the environment and how the organization currently manages it (Brorson and Larsson 2011). EIA is used to predict the environmental effects of an activity, project, or new technology (Noble 2015). LCA is a systematic, iterative, and comprehensive method that considers all stages in

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the lifecycle of a product, starting from the extraction of raw materials through transportation, production, use, recycling, and the final disposal of a product (Baumann and Tillman 2004).

Out of the multiple methods, LCA has been found to be suitable for assessing product-level environmental impact by applying lifecycle thinking. This makes LCA the predominant methodology for the evaluation of environmental impact at a product-level (Despeisse et al. 2022). Moreover, LCA has been used to quantify the environmental impact of the extraction and production of minerals and metals. For instance, Haque and Norgate (2013) used LCA to assess ferroalloy production in Australia and identified that approximately 60% or more of the total greenhouse gas emissions originated from coke and coal consumption. Similarly, Guimarães da Silva et al. (2018) used LCA on a coal mining and processing site and estimated that 3.29×10^{-2} $kgCO_2$-eq of impact to produce 1 kg of coal. Furthermore, their study identified that diesel consumed during the process was the most influential parameter through a sensitivity analysis. In the case of CRMs, several studies have used LCA. Lai et al. (2021) applied LCA to quantify the environmental impacts of producing 1 ton of flourspar concentrate (from mining, transport, and ore beneficiation processes), resulting in 174 $kgCO_2$-eq impact. The study further highlighted that one of the major environmental hotspots was the consumption of diesel in on-site transport machinery and electricity generation. Farjana, Huda, and Mahmud (2019) used LCA to assess the production of 1 kg of cobalt metal, resulting in 11.73 $kgCO_2$-eq impact. Furthermore, their findings indicated that the electricity consumption during the production process was the major contributor. In the case of Rare Earth Elements (REEs), Zapp et al. (2022) conducted a review of the LCA studies on REEs, and the study reported that 1 kg of neodymium extracted from multiple ore types and geographical locations resulted in an impact ranging between 61 and 115 kgCO2-eq. Overall, due to the differences in the system boundary of LCA assessing different minerals and metals, it is difficult to draw comparisons.

Rahimpour Golroudbary, Iryna, and Kraslawski (2023) utilized LCA to quantify the key environmental impacts during the production of magnesium. Zhang et al. (2019) used LCA to compare the environmental impact of producing erbium and scandium oxide, finding that the primary contributors to the environmental impact were the chemicals consumed during the production process. In addition, several other studies, such as Vahidi, Navarro, and Zhao (2016), Bailey et al. (2020), Sprecher et al. (2014), Pell et al. (2019b), Arshi, Vahidi, and Zhao (2018), and Yang et al. (2019) have used LCA to assess the production of REEs. A commonality among the results presented in the LCA studies is that the predominant source contributing to environmental impact often depends on the characteristics of each mining and mineral processing site. The site characteristics include the production volume, throughput, ore grade, size fraction of the mineral products, processing circuit, and type of machinery used at the site. The predominant sources of environmental impact are commonly explosives consumed in blasting, diesel consumed in ore handling, and energy and chemicals consumed in production (i.e. comminution, classification, and metallurgical processes).

In recent years, several studies in the mineral industry have explored the possibility of combining process simulation and LCA. An advantage of using process simulation is that it assists in reducing uncertainty in LCA (Segura-Salazar and Tavares 2021). For instance, Rinne et al. (2022) used process simulation-based LCA to compare the environmental impacts of different cyanide-free chloride processing routes during the production of gold. In the study, the authors used process simulation to generate Life Cycle Inventory (LCI) data. LCI data refers to the data concerning the consumption of resources, waste generation, and emissions during the life cycle of a product (Toniolo et al. 2020). Lappalainen et al. (2024) and Abadías Llamas et al. (2019) used the mass and energy balances from process simulation to develop consistent LCI for assessing the production of lithium hydroxide monohydrate and copper, respectively. In certain cases, simulation is used to complement the data collected from the site and literature. For instance, Beylot et al. (2021) used data collected from onsite tests, which were completed with additional calculations using process simulation to quantify the environmental impact of producing lead concentrate. Pell et al. (2019a) used data from the literature on the mining phase and simulation results to generate data on energy and material flows for the mineral processing phase to conduct the LCA for an REE project in the pre-feasibility stages. Other notable studies include Nan et al. (2024) and Rinne, Elomaa, and Lundström (2021) where the authors integrated process simulation and LCA to investigate oxidative pressure leaching and producing battery-grade cobalt sulfate, respectively. From the literature, it can be inferred that the process simulation has been mainly used to generate and compile LCI data to conduct LCA calculations. Additionally, the processing circuit assessed in these studies is often fixed.

A study by Sidorenko, Sairinen, and Moore (2020) presented a conceptual analysis of technologically advanced (non-artisanal) small-scale mining. The authors discuss the possibility of flexible and modular processing technology that can be easily deployed and moved between sites to extract ore from high-grade deposits. The various grade and size fractions of ore products produced from a flexible and modular small-scale mining set-up can have different environmental impacts due to differences in resource consumption and waste generation. This study investigates the environmental and economic aspects of a small-scale mining operation that produces various grades (high grade: >90%, medium grade: 80% to 85%) and size fractions of celestine minerals (hereafter referred to as celestine) using a flexible processing circuit setup. Additionally, Mesa et al. (2025) identified the need for environmental assessment of Strontium production, which in turn requires evaluating the environmental impact of celestine. To address this, a case study was developed on a celestine mine operated by Canteras Industriales located in Montevive, Spain. The main characteristic of the mine is the use of diesel-driven mobile machinery, such as wheel loaders, a mobile crusher, and screen and excavators in the processing circuit. These machines are used due to the flexibility they offer during the ore handling and processing operations. This flexibility enables the mine to tailor the processing circuit to handle Run-of-Mine (RoM) ore with different grades. This setup enables the production of multiple-size fractions of celestine, driven by size-specific prices. In addition to this, the mine is equipped with a pilot plant to valorize the tailings and enhance resource utilization. The economic aspect in this study focuses on estimating potential revenue from producing multiple grades and size fractions of celestine, and the social aspects are excluded from this study.

The research questions investigated in this study are as follows,

(1) What is the relationship between the processing circuit configurations and the environmental impacts?
(2) How does integrating tailings enrichment affect the environmental and economic performance of celestine?

Methodology

This section describes the two methods used in this study: LCA and simulation-supported LCA. It also describes how both methods were implemented.

Life cycle assessment

LCA involves four main phases: goal and scope definition, inventory analysis, life cycle impact assessment, and interpretation (Toniolo et al. 2020). This study has followed ISO 14040 and 14044 standards to conduct LCA (ISO 2006a, 2006b).

Goal and scope definition

The goal of the LCA study was to quantify the environmental impact of celestine with different grade and size fractions produced from different circuit configurations. In this study, a cradle-to-gate system has been assessed, encompassing operations such as ore extraction, transport to the processing site, and the production process. The functional unit for quantifying environmental impacts is 1 tonne of celestine.

Inventory analysis

Inventory analysis, also known as Life Cycle Inventory (LCI) analysis, involves collecting and compiling data concerning resource consumption, waste generation, and emissions during ore extraction, ore transportation, and production processes. For this study, data on the consumption of different resources and waste were collected through site visits and bills for the reference period of 2021. The reason for collecting the data over a period of one year is typically to capture seasonal variations in production, resource consumption, and emissions that might occur due to factors such as operational fluctuations, ore properties variation, market fluctuations, or periodic maintenance activities. The LCI datasets used for the modeling of consumption of different resources and waste are the modular LCA of each resource consumed and waste generated at the site. The datasets were developed using the GaBi 2021 and ecoinvent 3.6 databases, encompassing the environmental impacts originating from the relevant process steps or technologies over the supply chain of the different resources and waste. See Appendix C for the description of each dataset used for modeling different resources and waste. The LCI datasets used for modeling resources and waste are limited to the EU-28 geographical boundary, except that electricity is modeled using a data record that represents the Spanish residual grid mix. The sensitivity study on the LCI datasets is not considered within the scope of this work.

Impact assessment

Impact assessment, also known as Life Cycle Impact Assessment (LCIA), aims to translate the effects of resource consumption and waste generation quantified during inventory analysis in the form of an environmental impact category (Baumann and Tillman 2004). In this study, LCIA was performed using the characterization models (See Appendix D) included in the Environmental Footprints (EF) 3.0 reference package, which aligns with the midpoint-oriented impact pathway. Using this reference package, several impact categories can be quantified, and in this study, the chosen impact categories are as follows: Global Warming Potential – total (GWP – total) quantifies the total impact of greenhouse gases (CO_2, CH_4, CFCs, HCFCs, etc.) on global warming. Acidification Potential (AP) quantifies species (SO_2, H_2S, etc.) contributing to acid rain and acidification of soil, lakes, and other natural bodies. Eutrophication Potential (EP) focuses on nitrogen and phosphorus species and indicates how adding nutrients to freshwater contributes to upsetting the balance of the ecosystem. Photochemical Ozone Creation Potential (POCP) mainly consists of halogenated compounds that cause ozone loss in the stratosphere, and Abiotic depletion of fossil resources potential (ADP – fossil).

Interpretation

This is the final phase in LCA, where the results from LCI, LCIA, or both are summarized and discussed (ISO 2006a). During this phase, the results are analyzed to identify the primary contributors to environmental impact, such as specific processes, resources, or waste. This analysis can also uncover any errors or missing data. It provides a basis for conclusions, recommendations, and decision-making following the goal and scope definition.

Allocation

Allocation is the process of partitioning resources and waste among different products. This enables the differentiation of the environmental impact of celestine with different grade and size fractions. In this study, allocation is performed at two levels. The first level involves partitioning resources consumed and waste among operations, such as ore extraction, ore transportation, and production processes. This was performed based on the type of resource and its usage in machines used for different operations (see Appendix A for further description). This was necessary to quantify the environmental impact originating from each operation. The second level involves partitioning the resources consumed and waste generated during the production process among celestine with different grades and size fractions; this is where the process simulation results were utilized.

Automatic allocation tool

An automatic allocation matrix generated from simulation combined with LCA was used in this study to quantify the environmental impact of size and grade-specific celestine production. One of the challenges in LCA studies is tracking and collecting resource consumption and waste data, which is often limited at the site, especially if it requires instruments. Alternatively, manual data recording of resource consumption is also limited in many sites during regular operations. To address these challenges and generate an allocation matrix for LCA, the software *Plantsmith* was used. *Plantsmith* is an online software designed to assess the sustainability of products from a mining and quarrying site (Asbjörnsson et al. 2024).

In *Plantsmith*, the production process for celestine is mapped to the physical process at the site and represented through steady-state process simulation. To develop the process simulation, the unit models representing machineries such as mobile crushers, screens, conveyors, pumps, bins, splitters, and others were used. The process and unit models were tuned based on the production data (Bhadani et al. 2021). The software simulates the process until an equilibrium for mass and energy is achieved (Bhadani et al. 2021). The simulation results are used to develop an allocation matrix. The allocation matrix distributes the resources consumed and waste generated during the production process among the different fractions of celestine. The specific energy distribution in the circuit serves as a proxy for the allocation of electrical energy. Other resources and waste are allocated based on mass. This allocation matrix is used in the LCA, which helps to differentiate the environmental impacts among different grades and size fractions of celestine. Along with the process simulation and generation of the allocation matrix, the environmental impacts from producing celestine were quantified on *Plantsmith* using the LCI datasets.

Case study description

The operations at the mine include ore extraction through blasting and excavators, loading and hauling of the ore to the processing site, and the production process involving crushing and size classification in a mobile circuit and additional tailings enrichment process. A wheel loader is used to transport the material between different processing machines in the circuit. The main characteristic of the mine was its capability to tailor the processing circuit to transform high-grade (>90% celestine) and medium-grade (80–85% celestine) RoM ores into celestine. This meant that the site could operate with multiple modes of operation (i.e. different processing circuits).

The celestine produced from different processing circuits can have distinct environmental impacts due to variations in resource consumption and differences in waste generation during the production processes. The choice of processing circuit is influenced by market demands since celestine with varying grades and size fractions correspond to differences in price. Apart from the existing operational flexibility and price differences, the mine processing capability is being expanded to include tailings enrichment processes due to degrading ore quality and the need to valorize old tailing deposits. The tailings enrichment process is at a pilot scale and consists of desliming and Dense Media Separation (DMS) processes.

Four scenarios were developed and assessed. Each scenario dealt with different processing circuits producing celestine with varying grade and size fractions. For each scenario, a process simulation model was developed to quantify the environmental impact of different celestine. Table 1 presents the RoM ore properties used for the simulation.

Table 1. RoM ore properties (HG – High grade, MG – Medium grade).

Material property	Value	Unit
Mass flow	147	tonne/hour
Moisture	2	%
Bulk Density	HG – 3.70 MG – 2.45	tonne/m^3
Work index	12	kWh/tonne
F80	57	mm

The following sections briefly describe the processing circuits assessed under the four scenarios.

Scenario 1

Scenario 1 was developed based on the circuit used for processing high (>90%) and medium grade (80% to 85%) celestine ore, both producing <35 mm celestine. This scenario serves as a baseline based on the extraction and processing operations at the mine during the reference period (2021). This scenario was further divided into two cases, i.e. cases a and b, which dealt with processing high-grade and medium-grade ore, respectively.

Case a

Figure 1 illustrates the processing circuit with the operations involved in processing high-grade (>90%) ore to produce the <35 mm. After blasting, the visually selected ore, representing high grade, is loaded onto a dumper truck and transported to the processing site. Subsequently, the ore goes through the size reduction process in a mobile crushing plant, starting with crushing in a mobile crusher, producing a <100 mm fraction. This fraction is further reduced in size by feeding it through a crushing bucket fitted onto the excavator's arm, producing the <35 mm high-grade celestine.

Case b

Figure 2 illustrates the circuit processing medium-grade ore to obtain a <35 mm celestine. The processing steps involved until the production of the <100 mm fraction are similar to those of high-grade ore processing. In the case of medium-grade ore, <100 mm was first screened on a mobile screen, resulting in two fractions: fine (<6 mm) and coarse (+6 −40 mm). The coarse fraction was reduced in size by feeding it through a crushing bucket to produce a coarse fraction (<35 mm) and a fine fraction (<6 mm). The coarse and fine fractions were classified as celestine and tailing, respectively. The key differences between high-grade and medium-grade ore processing were the use of the mobile screen and the number of trips needed from the ore extraction site to the processing site due to differences in quantity, density, and tailings production.

Scenario 2

Scenario 2 was developed based on the capability of the site to tailor the processing circuit to obtain different size fractions of celestine. The circuit shown in Figure 3 was utilized during

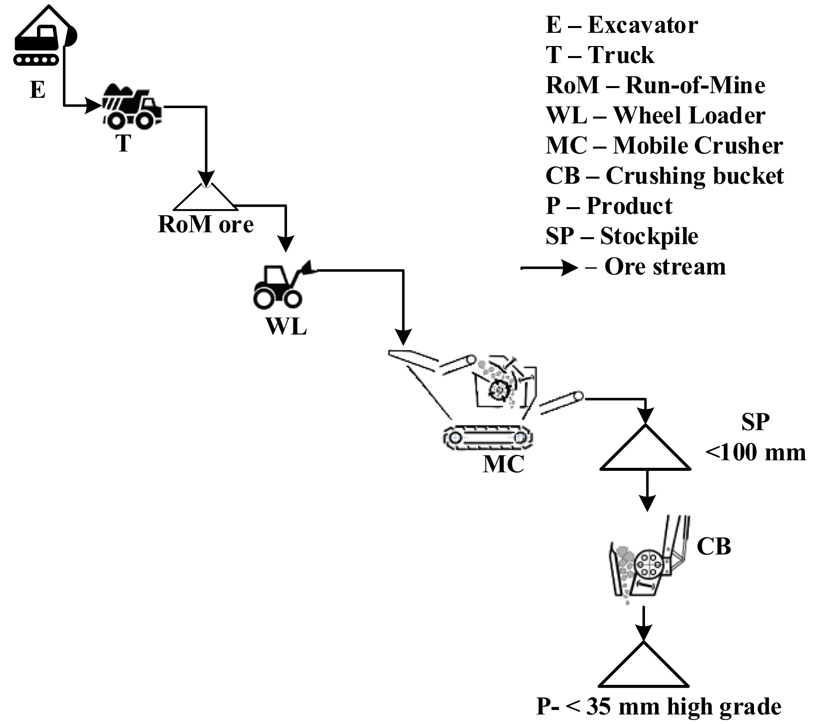

Figure 1. Case a - processing circuit for high-grade ore.

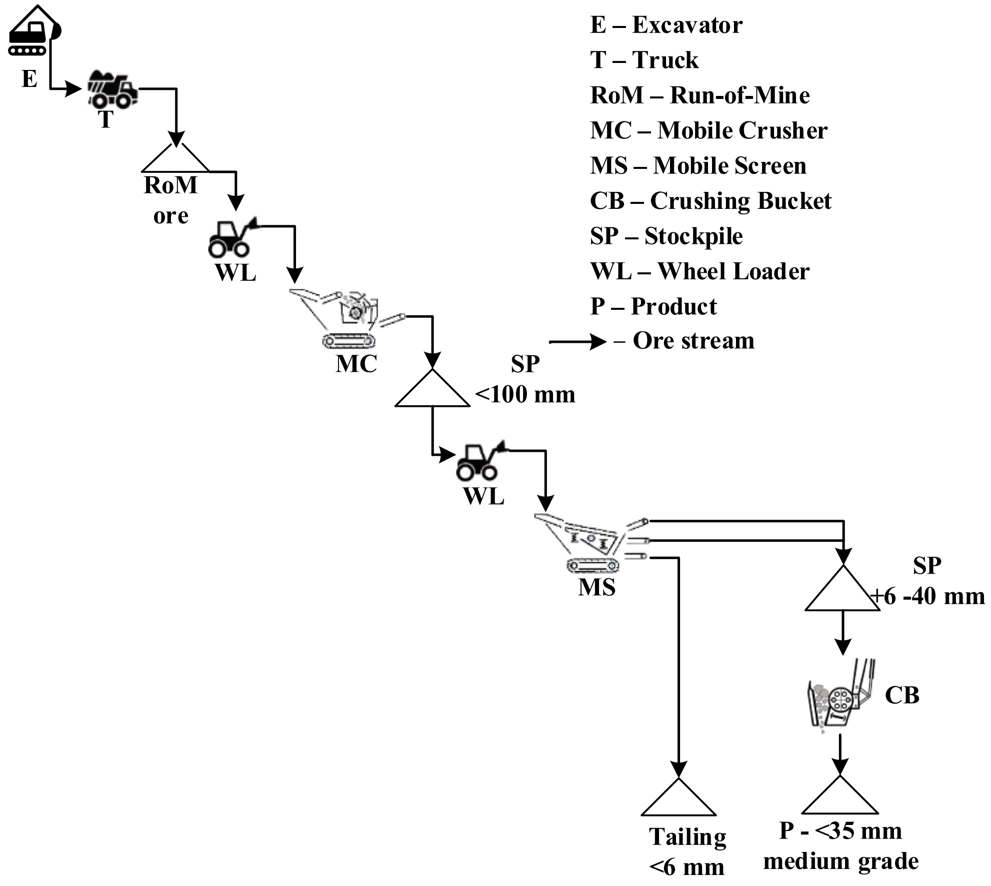

Figure 2. Case b - processing circuit for medium-grade ore.

a batch process, resulting in <35 mm and +6 –20 mm celestine. The reason behind producing the +6 –20 mm was its price, which was higher than that of the <35 mm. During the batch process, the quantity of the <35 mm and +6 –20 mm was estimated to have a distribution of 53.8% and 46.2%, respectively. The annual production of <35 mm and +6 –20 mm was estimated utilizing

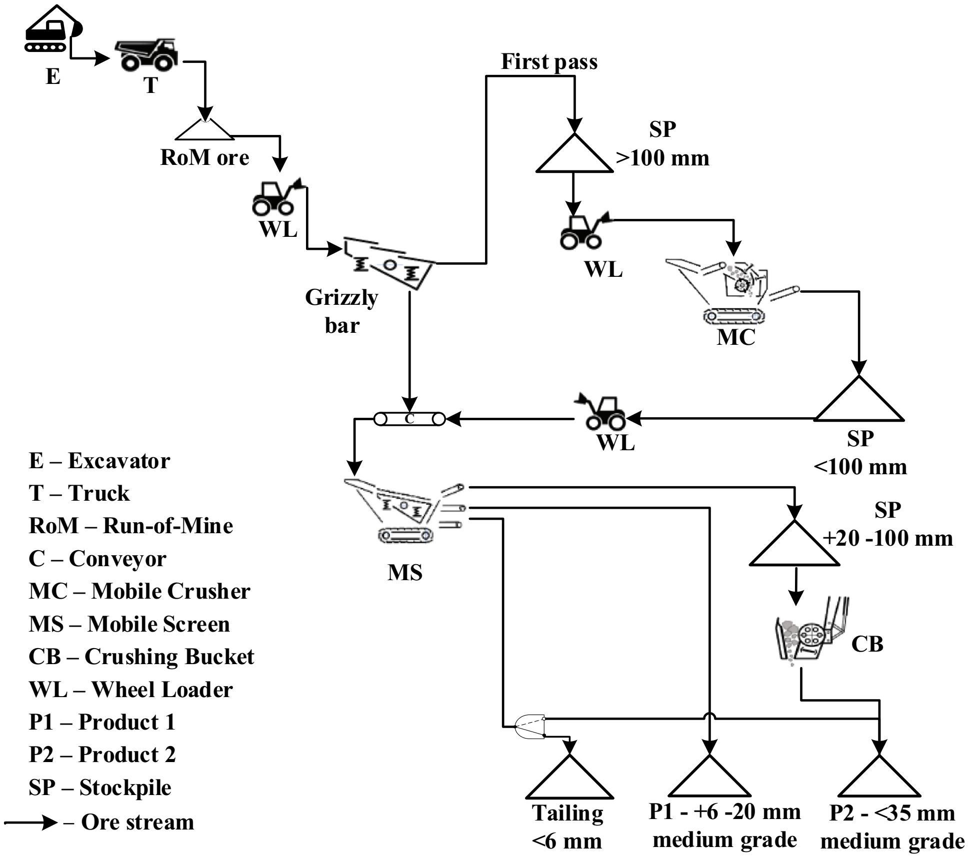

Figure 3. Processing circuit assessed in scenario 2.

this information, coupled with an assumption that, in scenario 2, only medium-grade RoM ore is processed.

Figure 3 illustrates the process circuit assessed under scenario 2. First, an excavator extracts medium-grade celestite ore and loads it onto a dumper truck for transport to the processing site. At the processing site, the RoM ore goes through a coarse size classification process using a mobile screen fitted with a grizzly bar, resulting in two fractions: >100 mm and <100 mm. The >100 mm fraction was fed to a mobile crusher to reduce the size and obtain a <100 mm fraction. The <100 mm fraction from the grizzly bar and the mobile crusher undergoes a further size classification process in the same mobile screen, resulting in three material fractions: coarse (+20 −100 mm), medium (+6 −20 mm), and fine (<6 mm). The medium and the fine fractions required no further processing and were directly classified into +6 −20 mm celestine and tailings, respectively. The coarse fraction is further reduced in size in the bucket crusher to produce <35 mm celestine (i.e. P2).

Scenario 3

This scenario is an expansion of scenario 1 (case b) by including the tailings enrichment process (see Figure 4). As described in Case b, the <6 mm fraction was produced from the mobile crushing and size classification process circuit. This fraction was classified as tailings and later enriched at the pilot plant, which consisted of desliming and DMS processes to recover a medium-grade +1 −6 mm celestine. The tailings enrichment process began in a desliming unit that deslimes <6 mm tailings to remove material <200 μm (consisting mainly of clay particles) by utilizing a screw conveyor. The fraction >200 μm from a screw conveyor was later fed through a vibrating screen to remove any oversize material >6 mm, thus resulting in two material fractions: oversize (>6 mm) and fine (+200 μm −6 mm). The <200 μm and >6 mm fractions were categorized as non-hazardous tailings. The fine fraction +200 μm −6 mm from the desliming unit was transported by wheel loader to the DMS plant, where it was mixed with ferrosilicon (FeSi) material and water to conform to a mixture of a density between 2.7–2.9 kg/L. Mix fed to an inclined hydrocyclone (5°-25°) where separation occurs due to the difference in density between the celestine ore (3.96 kg/L) and the gangue consisting mainly of calcite (2.90 kg/L). This separation process resulted in two material fractions: a dense underflow with celestine and a light overflow with inert material (i.e. +1 −6 mm). The underflow stream was later fed through the lower deck of the vibrating screen to separate the celestine from the mixture of Ferrosilicon (FeSi) and water, recovering celestine with a bulk density of up to 3.96 kg/l and a grade of 80–83%. Since the process operated in a closed circuit, the FeSi and water were recirculated back into the separation circuit (see Figure 4).

Scenario 4

Figure 5 illustrates the processing circuit assessed in scenario 4. The main reason for developing this scenario was to assess the influence of producing three different-size fractions of celestine compared to two in scenario 3. The processing circuit assessed

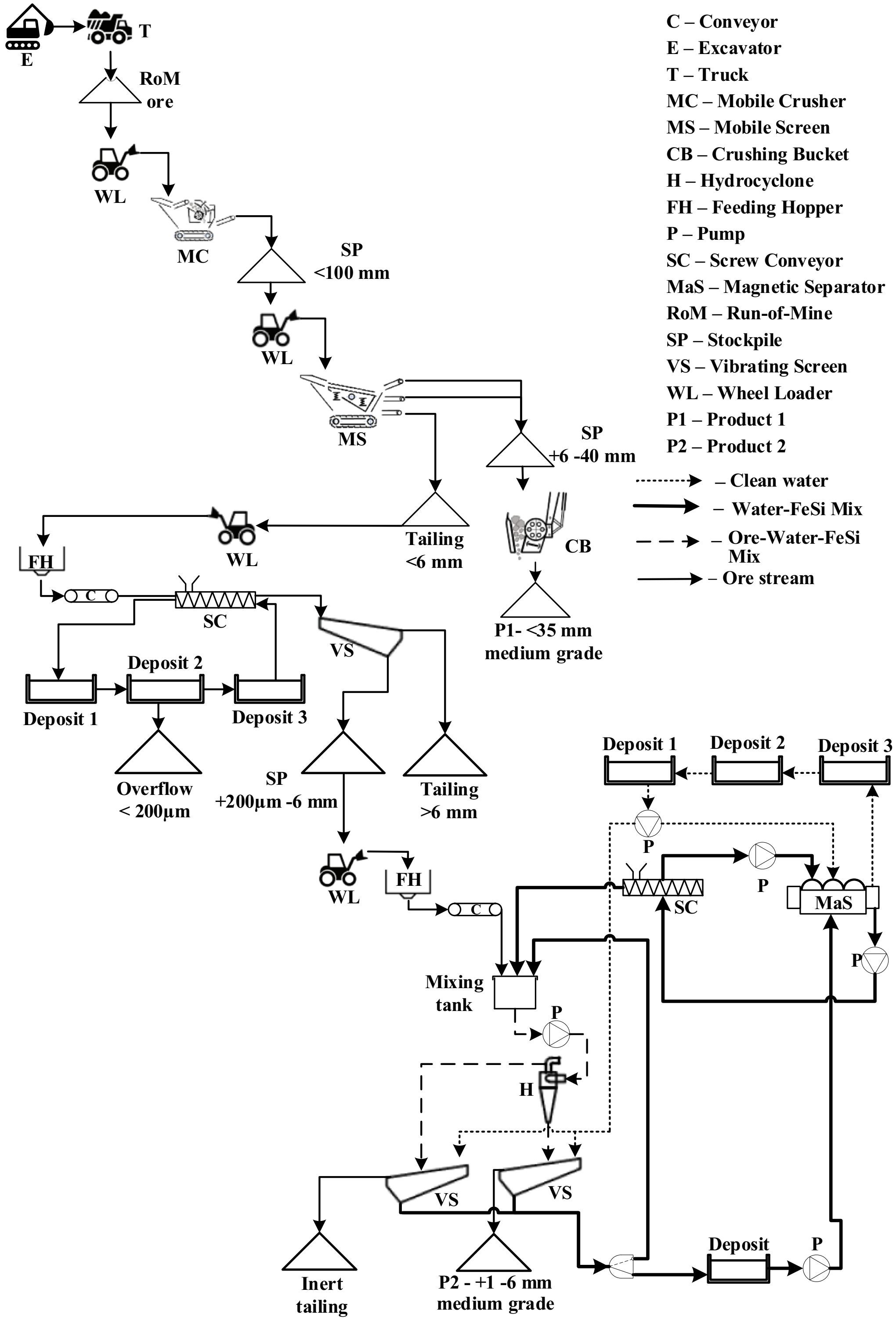

Figure 4. Processing circuit assessed in scenario 3.

in this scenario is the expansion of scenario 2 by including the tailings enrichment process to enrich <6 mm. The enrichment process is the same as the one described in scenario 3.

Data estimation

Table 2 provides a summary of the differences among the different circuits assessed in the four scenarios.

Table 3 presents the production, resources consumed, and waste data for the four scenarios. As for scenario 1, the data was based on the operations at the site. It serves as the baseline scenario, showcasing how the mine operated. The data concerning scenarios 2, 3, and 4 were estimated based on the baseline case, assuming that the total quantity of RoM ore processed in each scenario is 222,148 tonnes per year. The data concerning the consumption of different resources and

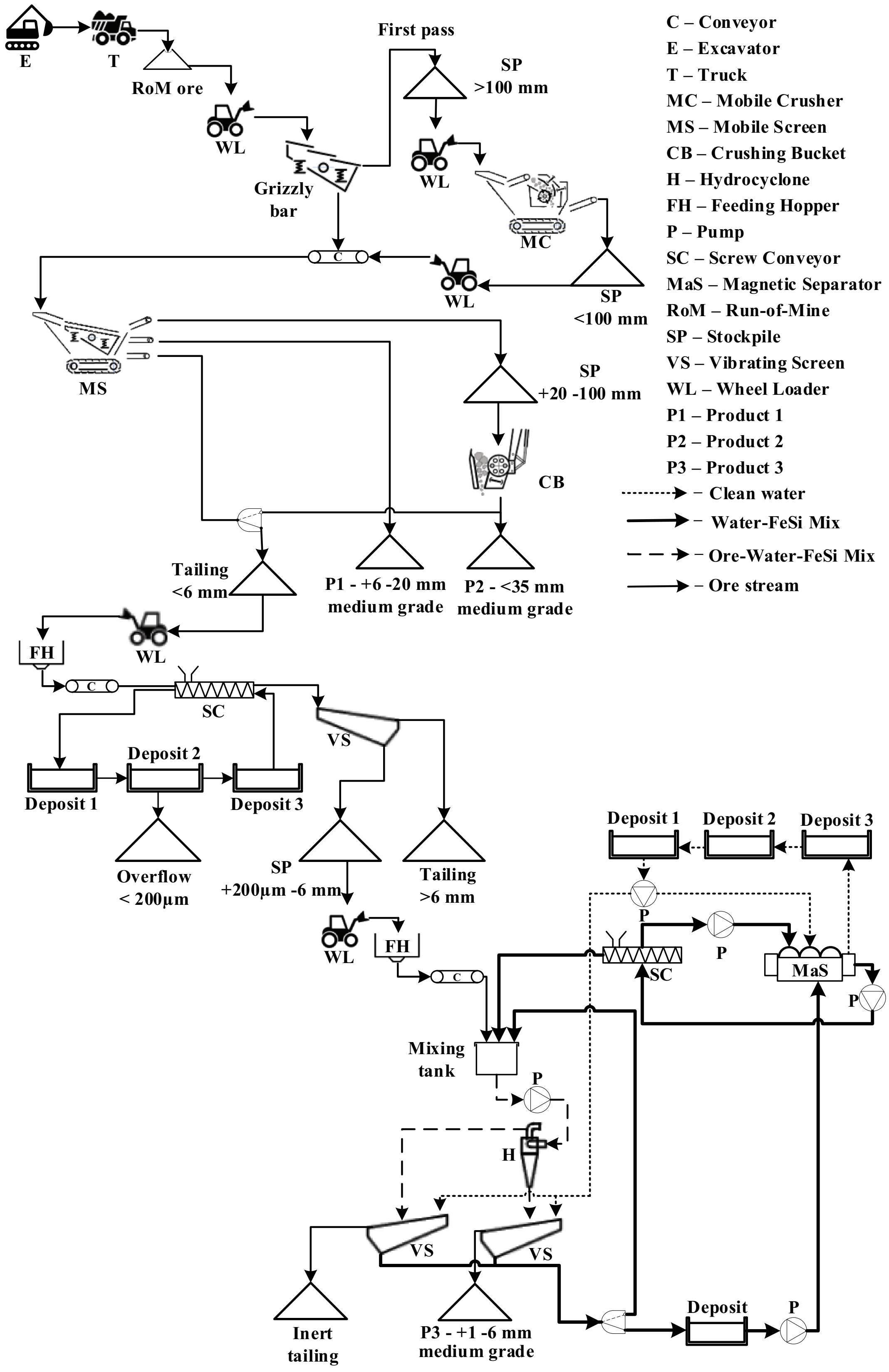

Figure 5. Processing circuit assessed in scenario 4.

Table 2. Summary of differences among the processing circuits assessed in four scenarios (HG – High grade, MG – medium grade).

	Scenario 1				
Parameter	Case a	Case b	Scenario 2	Scenario 3	Scenario 4
Grade of the RoM ore	HG ore	MG ore	MG ore	MG ore	MG ore
Size fraction of celestine	<35 mm	<35 mm	<35 mm +6 –20 mm	<35 mm +1 –6 mm	<35 mm +6 –20 mm +1 –6 mm
Size fraction of tailing waste	Tailing is not produced	<6 mm	<6 mm	<200μm +1 –6 mm >6mm	<200μm +1 –6 mm >6mm
Tailing enrichment	Not included	Not included	Not Included	Included to produce +1 –6 mm celestine	Included to produce +1–6 mm celestine

Table 3. Resource and waste data for the four scenarios.

		Scenario 1				
Production, Resources, and Waste	Unit	Case a	Case b	Scenario 2	Scenario 3	Scenario 4
Input RoM	tonne/year	14,641	207,507	222,148	222,148	222,148
<35 mm celestine	tonne/year	14,641	165,957	95,585	177,666	95,585
+6 –20 mm celestine	tonne/year	–	–	82,082	-	82,082
+1 –6 mm celestine	tonne/year	–	–	–	21,797	21,797
Tailings	tonne/year	–	41,550	44,482	22,685	22,685
Diesel	liters/year	5,111	59,349	62,633	86,883	85,883
Electricity	kWh/year	1,576	17,862	19,122	36,371	36,371
Water	m^3/year	199	2,261	2,421	12,800	12,800
Explosives	kg/year	803	9,097	9,900	9,900	9,900
Lubricants	liters/year	165	2,420	2,457	2,909	2,758
Metals	kg/year	587	6,649	7,118	7,991	7,991
FeSi	kg/year	–	–	–	65,391	65,391
Rubber	kg/year	10	115	123	138	138
Chemicals	liters/year	16	184	197	221	221
Plastics	kg/year	8	92	98	111	111
Total non-hazardous waste	kg/year	56	632	677	760	760
Total hazardous waste	kg/year	89	1,011	1,082	1,215	1,215
Inert rock waste	tonne/year	2	41,569	44,501	22,704	22,704

waste were estimated (see Appendix B for a detailed description of the estimation model used in this study).

Results

The following section presents the results of the process simulation and LCA.

Particle size distribution

Figure 6 shows the Particle Size Distribution (PSD) results obtained from the process simulation using *Plantsmith* for scenarios 1, 2, 3, and 4, respectively. Figure 6 presents the PSD curves for the RoM ore and different-size fractions of celestine and tailings produced in each scenario. In addition to PSD results, another key output from the simulation was an automatically generated allocation matrix used for conducting LCA.

Allocation

Table 4 presents the results for the first level allocation, where the resources and waste were partitioned among the different operations. Table 5 presents the second level of allocation developed based on the simulation results, where the resources consumed and waste generated during the production process were partitioned among multiple-size fractions of celestine. Using these allocation matrices enabled the differentiation in the environmental impact among different grade and size fractions of celestine produced in four scenarios. By utilizing the allocation matrices presented in Table 4 and 5 and calculating the consumption of resources and waste generation to produce 1 tonne of celestine (see Appendix E), the cradle-to-gate environmental impacts for producing 1 tonne of celestine were quantified.

Life Cycle Assessment

The cradle-to-gate environmental impacts for producing 1 tonne of celestine were quantified for each scenario. From Figure 7, it can be observed that, for producing <35 mm and +6 –20 mm celestine in scenarios 1, 2, 3, and 4, the majority of the cradle-to-gate GWP – total impact originated during ore transportation, which included transport from the extraction site to the production site and the transport of material between different processing equipment. The contribution from ore transportation ranged between 53% and 54% of the cradle-to-gate GWP – total impact category. In contrast, nearly 88% of the impact for producing +1 –6 mm celestine in scenarios 3 and 4 originated from the production process. This was attributed to the consumption of resources such as FeSi in the DMS plant and diesel in different processing machineries (i.e. crusher, screen, and other equipment at the DMS plant). Similar results were

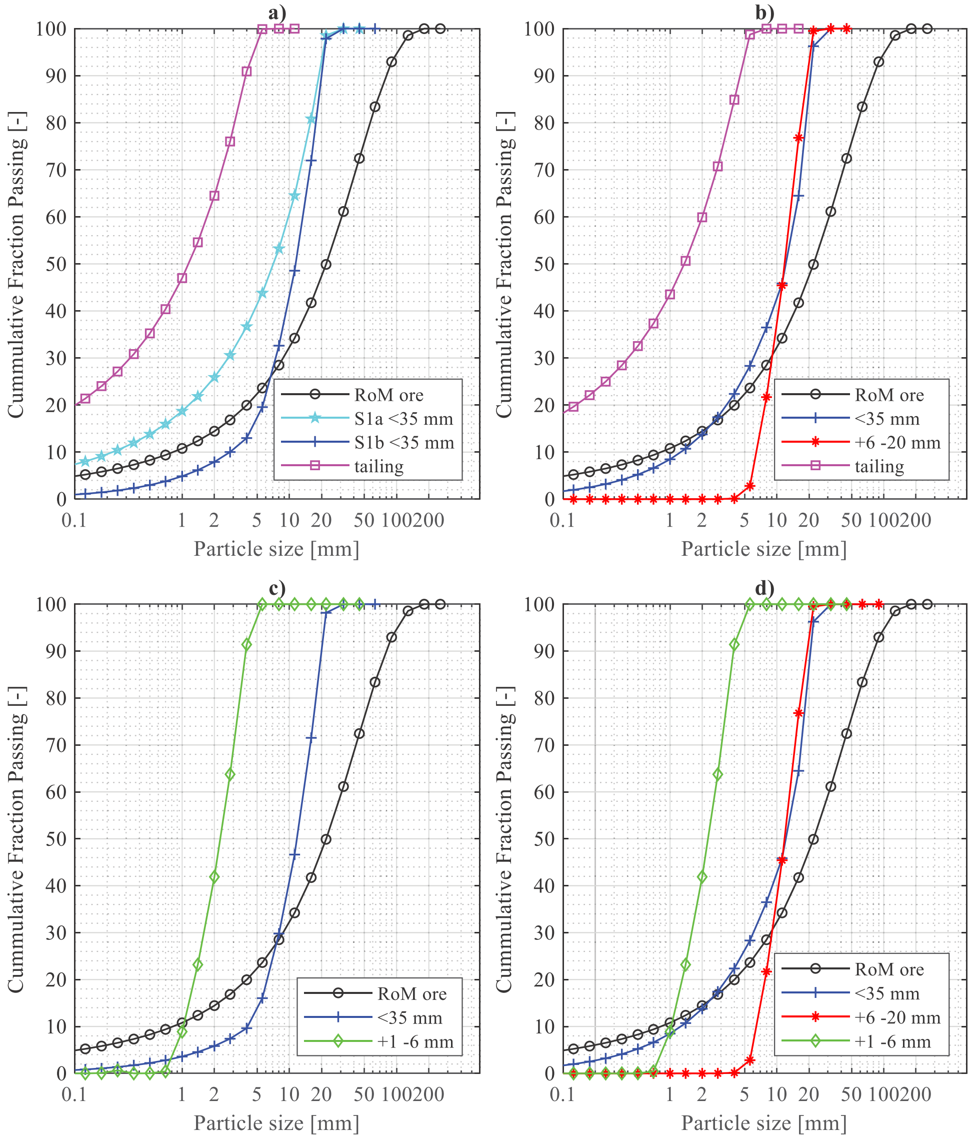

Figure 6. PSD for different fractions of celestine produced in scenarios: a) scenario 1 with cases a and b (HG - High grade, MG - Medium grade), b) scenario 2, c) scenario 3, and d) scenario 4.

observed in the case of other studied impact categories, where most of the impact originated from ore transportation for producing <35 mm and +6 −20 mm celestine produced in scenarios 1, 2, 3, and 4 (see Appendix F).

Figure 8 presents the cradle-to-gate GWP – total (kgCO$_2$-eq./tonne) impact for the different grade and size fractions of celestine produced in scenarios 1, 2, 3, and 4. The results show that the cradle-to-gate impact for producing 1 tonne of <35 mm and +6 −20 mm celestine resulted in a lower impact in scenarios 3 and 4 compared to scenarios 1 (case b) and 2. This is due to the production of an additional size fraction of celestine, in this case, +1 −6 mm celestine production in scenarios 3 and 4. In the case of <35 mm celestine, the impact was lower in scenario 3 (1.27 kgCO$_2$-eq./tonne) in comparison with scenario 1 (case b) (1.33 kgCO$_2$-eq./tonne). This is because, in scenario 1 (case b), all of the resources consumed and waste were allocated to <35 mm, since it was the only economically viable product, and the <6 mm fraction was treated as non-hazardous tailing. In scenario 3, on the other hand, the <6 mm tailing was enriched to produce +1 −6 mm celestine, thus leading to the allocation of the resources consumed and waste among the <35 mm and +1 −6 mm. A similar observation can be made between scenarios 2 and 4, where the production of <35 mm and +6 −20 mm in scenario 4 resulted in a lower (1.22 and 1.21 kgCO$_2$-eq./tonne, respectively) impact in comparison to that of scenario 2 (1.29 kgCO$_2$-eq./tonne).

LCA results show that using different processing circuits influences the environmental impact of celestine produced in the four scenarios. Additionally, the results show that the processing circuit producing multiple-size fractions of celestine leads to a lower environmental impact. For instance, when comparing the circuits assessed in scenario 1 (case b) and scenario 2, it was found that the cradle-to-gate environmental impact in scenario 2 (1.29 kgCO$_2$-eq./tonne) was 3% lower than that of scenario 1 (case b) (1.33 kgCO$_2$-eq./tonne). This difference is attributed to the fact

Table 4. Allocation of resources consumed and waste generated among different operations (in percentage).

	Scenario 1														
	Case a			Case b			Scenario 2			Scenario 3			Scenario 4		
Resources and waste	Ore extraction (%)	Ore transportation (%)	Production process (%)	Ore extraction (%)	Ore transportation (%)	Production process (%)	Ore Extraction (%)	Ore Transportation (%)	Production process (%)	Ore Extraction (%)	Ore Transportation (%)	Production process (%)	Ore Extraction (%)	Ore Transportation (%)	Production process (%)
Diesel	27	67	6	26	65	9	26	65	9	19	62	19	19	61	20
Electricity	0	0	100	0	0	100	0	0	100	0	0	100	0	0	100
Water	100	0	0	100	0	0	100	0	0	19	0	81	19	0	81
Lubricants	26	61	13	20	47	33	20	48	32	20	48	32	21	50	29
Metal	0	0	100	0	0	100	0	0	100	0	0	100	0	0	100
Ferro silicon	–	–	–	–	–	–	–	–	–	0	0	100	0	0	100
Rubber	27	67	6	26	65	9	26	65	9	19	62	19	19	61	20
Plastic	0	0	100	0	0	100	0	0	100	0	0	100	0	0	100
Chemicals	0	0	100	0	0	100	0	0	100	0	0	100	0	0	100
Explosives	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0
Mixed waste	0	0	100	0	0	100	0	0	100	0	0	100	0	0	100
Hazardous waste	0	0	100	0	0	100	0	0	100	0	0	100	0	0	100
Inert Rock waste	100	0	0	1	0	99	1	0	99	1	0	99	1	0	99

Table 5. Allocation matrix of resources consumed and waste generated during the production process (in percentage).

	Scenario 1		Scenario 2		Scenario 3		Scenario 4		
	Case a	Case b							
Resources and waste	<35 mm	<35 mm	<35 mm	+6 −20 mm	<35 mm	+1 −6 mm	<35 mm	+6 −20 mm	+1 −6 mm
Diesel	100	100	54	46	30	70	17	13	70
Electricity	100	100	54	46	47	53	25	22	53
Water	100	100	54	46	0	100	0	0	100
Lubricants	100	100	54	46	87	13	50	39	11
Metal	100	100	54	46	89	11	48	41	11
Ferro silicon	–	–	–	–	0	100	0	0	100
Rubber	100	100	54	46	89	11	48	41	11
Plastic	100	100	54	46	89	11	48	41	11
Chemicals	100	100	54	46	89	11	48	41	11
Explosives	100	100	54	46	89	11	48	41	11
Mixed waste	100	100	54	46	89	11	48	41	11
Hazardous waste	100	100	54	46	89	11	48	41	11
Inert Rock waste	100	100	54	46	89	11	48	41	11

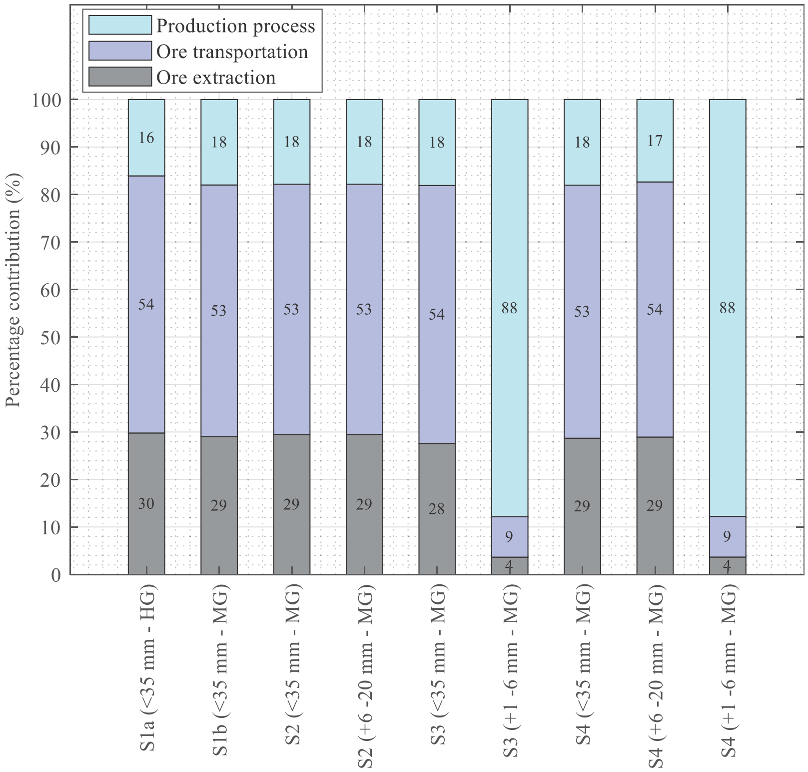

Figure 7. The percentage contribution from different operations in a cradle-to-gate system for GWP - total impact category for celestine produced in different scenarios (S - Scenario, HG - High grade, MG - Medium grade).

that the circuit in scenario 2 produces two size fractions of celestine (<35 mm and +6 −20 mm), whereas the circuit in scenario 1 (case b) produces only one fraction.

Although the <35 mm and +6 −20 mm celestine resulted in lower impact, the GWP – total impact of producing the +1 −6 mm in scenarios 3 and 4 was 9.62 and 9.57 $kgCO_2$-eq. /tonne, respectively. This was due to the consumption of additional resources, such as diesel and FeSi, during the tailings enrichment process.

Influence of the tailings enrichment process

To compare the environmental impact on the scenario level, a weighted average of the GWP-total impact for each scenario was calculated (see Figure 9a). It can be observed that the GWP-total impact of producing 1 tonne of celestine from scenario 3 (2.18 $kgCO_2$-eq./tonne) was 63% greater compared to scenario 1 (1.33 $kgCO_2$-eq./tonne) as a result of tailings enrichment. A similar observation was made in scenario 4, where the GWP-total impact (2.13 $kgCO_2$-eq./tonne) was 60% greater compared to scenario 1. Although the impact was higher, from Figure 9b, it can be observed that the enrichment of the <6 mm tailings in scenarios 3 and 4 led to a reduction in the quantity of tailings by 45%, reaching 22,685 tonne, compared to scenario 1 (41,550 tonne). Consequently, this led to an increase in the total quantity of celestine produced by 10% in scenarios 3 and 4 (199,463 tonne) compared with scenario 1 (180,598 tonne) (see Figure 9b).

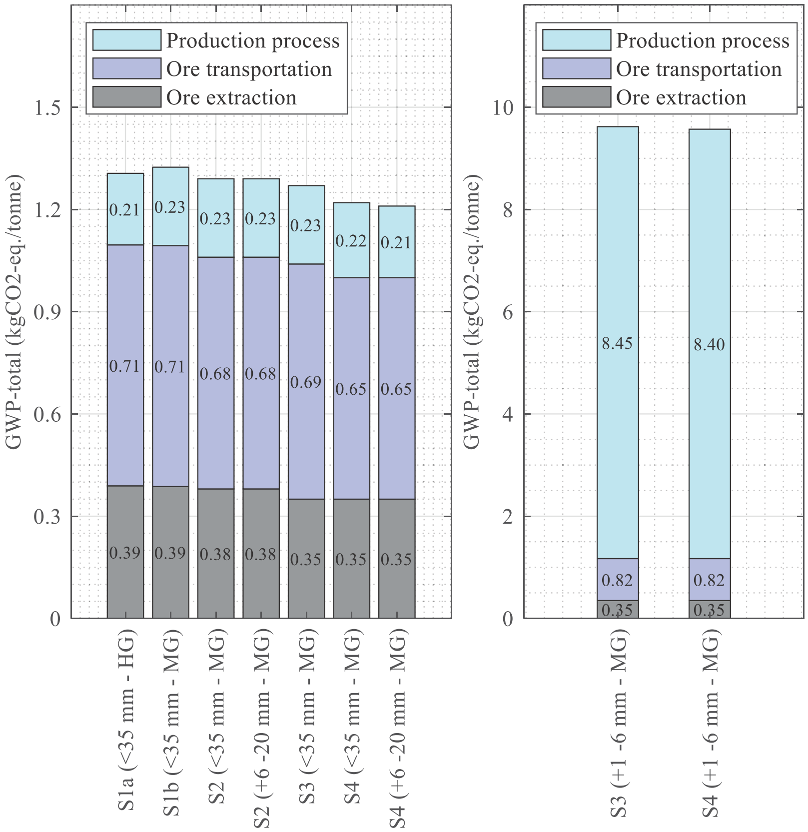

Figure 8. Results for GWP - total impact category for celestine produced in different scenarios (S – scenario, HG - High grade, MG – medium grade). Note: In Figure 8 the scale on the Y-axis differs because the GWP-total impact from the production of +1 −6 mm celestine in scenarios 3 and 4 was significantly greater than <35 mm and +6 −20 mm.

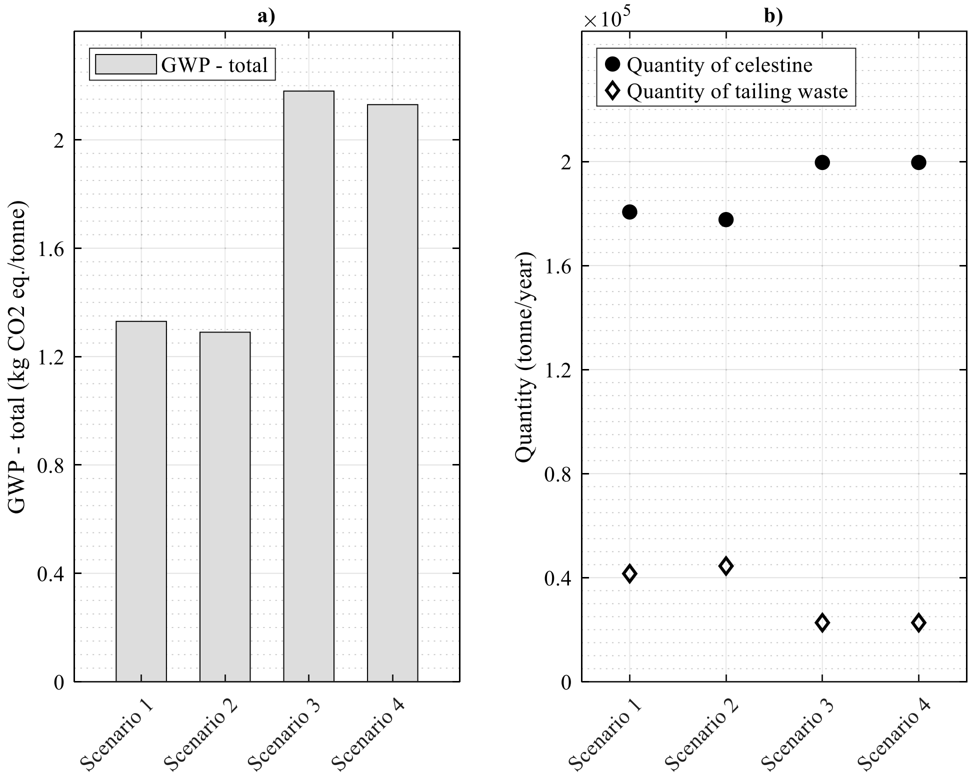

Figure 9. Correlation between GWP-total, tailing waste, and quantity of celestine: a) GWP-total impact, and b) quantity of product and tailing waste produced.

Further comparison was conducted by estimating revenue generation for each scenario. The revenue was estimated by considering the quantity of celestine produced and the corresponding scaled prices. Table 6 shows the data on the scaled price for celestine with different grades and size fractions. It can be observed that the price varies based on the grade and size fraction of celestine. The <35 mm fraction produced in scenario 1 (case a) had the highest price due to a higher grade (>90%). Among the medium-grade celestine, the +1 −6 mm from scenarios 3 and 4 was priced higher due to its fine size distribution. The coarsest medium-grade fraction, i.e. <35 mm, had the lowest price. Alongside this, a price associated with the storage of the tailings was also considered in the revenue estimation.

Figure 10a, b show the potential revenue generation and the quantity of the tailing produced in the four scenarios, respectively. From the results, it was clear that the revenue (calculated based on the scaled price) increased in scenarios 3 and 4 due to an increase in the production of economically viable celestine (i.e. +1 −6 mm). Compared to scenario 1, which generated a revenue of 91,747, scenario 2 showed a 2% increase in revenue (93,273), indicating a negligible improvement. Comparing scenarios 1 and 2, it can be observed that the minor adjustments to the circuits do not lead to a significant increase in revenue. Scenario 3 had a 14% higher revenue, reaching 104,286, than scenario 1, reflecting a more noticeable increase. Scenario 4 showed the highest revenue of 109,621, representing a 19% increase over scenario 1. These results demonstrate a clear trend of revenue growth across the scenarios when compared to scenario 1. Although the revenue calculations show a trend that process expansion with tailing enrichment generates higher revenue (see Figure 10a), it should be acknowledged that these numbers are indicative since the revenue is calculated based on the scaled prices.

Table 6. Scaled prices of the celestine produced in (HG – High grade, MG – medium grade).

Celestine	Scaled prices
<35 mm (HG)	0.66
<35 mm (MG)	0.52
+6 -20mm	0.59
+1 -6 mm	0.65
Tailing	−0.10

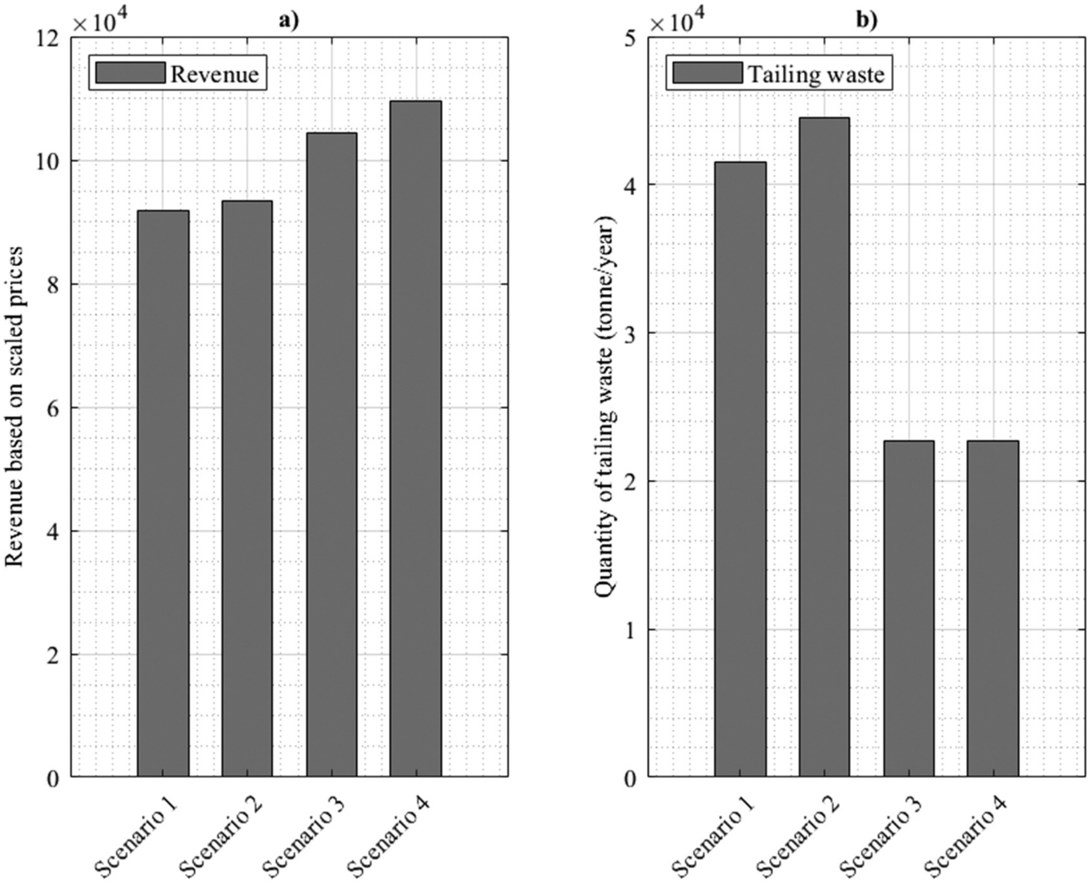

Figure 10. Revenue and tailing waste generated for scenarios 1, 2, 3, and 4: a) revenue and b) quantity of tailings waste.

Discussion

The LCA results show that incorporating tailings enrichment to produce +1 −6 mm celestine in scenario 3 led to a 63% increase in environmental impacts while yielding at least a 14% increase in revenue compared to scenario 1. This conclusion was drawn based on the assumption that each scenario processed 222,148 tonnes of RoM ore, enriching only 41,550 tonnes of tailings in scenario 3. However, the capacity of the tailings enrichment process in these scenarios can be expanded by processing the old tailings stored in the stockpile at the mine, potentially increasing revenue. Also, the significant increase in environmental impact was due to the consumption of FeSi and diesel. Consumption of diesel increased in scenarios 3 and 4 compared to scenarios 1 and 2, because of two factors: the operation of wheel loaders for transporting <6 mm tailings for enrichment, and the use of a diesel generator to supply electricity for the enrichment process at the DMS plant. The latter was the major contributor to the increased diesel consumption. If the electricity consumed at the DMS plant is sourced from the Spanish electricity grid, there is a potential to reduce the environmental impact of the tailings enrichment process.

The results show that using different processing circuits can lead to differences in the environmental impacts of celestine. These results are for the cradle-to-gate system boundary. The life cycle phase, such as the transportation of celestine to external actors, can lead to further differences in the impacts among the different grade and size fractions of celestine. The environmental impacts that occur during transportation can vary depending on the grade of celestine. For instance, transporting high-grade and medium-grade celestine, with bulk densities of 3.70 tonne/m^3 and 2.45 tonne/m^3, respectively, can have distinct environmental impacts. Assuming the same transportation distance and mode of transportation, the environmental impact of high-grade celestine can be lower than that of medium-grade celestine. This is because the higher bulk density of high-grade celestine allows fewer trips to transport the same quantity, reducing fuel consumption, emissions, and overall environmental impact.

The LCA conducted for each scenario was static, which implicitly assumed that the factors, such as resource consumption, emissions, and environmental effect mechanisms, remained constant during the reference period (2021). Along with this, factors associated with dynamic production, such as ore quality variation, equipment wear, and associated production variation, are considered constant based on the reference period data. These factors are both temporally and spatially dependent. For instance, the emission intensity of the supply chain of different resources may change due to technological developments. Also, characterization models for certain impact categories may vary across different geographical regions. Additionally, process-related variations, such as the consumption of components due to wear and variations in the frequency of maintenance, need to be considered. Such variations can be captured through the dynamic LCA (DLCA) framework. Conducting DLCA on producing different celestine products could provide new perspectives on environmental impacts.

An approach such as Multi-Criteria Decision-Making (MCDM) can be used to analyze the trade-off between LCA results and revenue calculation for different processing circuits. MCDM is a powerful approach in complex decision-making that comprehensively considers different conflicting criteria, such as those related to increased impact and revenue when adding the tailing treatment. In MCDM, other aspects, such as operating and investment costs, can be considered in the assessment. MCDM can potentially enable the choice of a favorable processing circuit depending on the input RoM properties and from both environmental and economic perspectives.

Conclusions

Using mobile machines, the mine can tailor the processing circuits to handle varying properties of RoM ore and produce multiple-size fractions of celestine. The study investigated the relationship between the process circuit configurations and the environmental impact of celestine. Using site-specific data combined with an automatic allocation matrix generated from simulation results enabled the quantification of environmental impact specific to different grade and size fractions of celestine produced using a flexible processing setup. It was found that the minor adjustments to the mobile crushing plant to produce multiple-size fractions of celestine resulted in a 3% lower GWP – total impact compared to the circuit producing a single-size fraction. This was mainly because of the allocation of resources and waste among the multiple fractions of celestine. Similarly, the revenue estimation showed a minor change (2% increase), indicating that the influence of minor circuit adjustments was limited.

Furthermore, including the tailings enrichment process to valorize the tailings produced from the mobile crushing plant led to a 63% increase in environmental impacts compared to the circuits without the tailings enrichment. This increase in impact was due to the consumption of resources such as FeSi and diesel. The increase in diesel consumption was attributed to burning diesel in a generator to produce the electricity needed for the enrichment process in the DMS plant. On the other hand, adding tailings enrichment resulted in higher production of celestine (by at least 10%) compared to circuits without tailings enrichment. From an economic perspective, an increase in production led to at least a 14% increase in revenue. Additionally, the valorization of tailings can lead to better utilization of natural resources, i.e. leading to a reduced extraction of natural raw material. Furthermore, enhancing the capacity of the tailing enrichment process presents an opportunity to reduce the environmental impact while increasing revenue. In conclusion, the results from the LCA, coupled with revenue estimation, assist in comparing the different processing circuits from environmental and economic aspects.

Acknowledgments

This study was performed under the project Rotate-Circular Ecological Essential & Critical Raw Materials project, under Grant Agreement ID: 101058651, funded by the EU Horizon Europe. This work has been performed within the Sustainable Production Initiative and the Production Area of Advance at Chalmers; this support is gratefully acknowledged.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the HORIZON EUROPE Digital, Industry and Space [Grant Agreement ID: 101058651].

Credit authorship contribution statement

Varun Gowda: Conceptualization, Formal analysis, Investigation, Data curation, Methodology, Visualization, Writing – original draft. **Kanishk Bhadani**: Conceptualization, Investigation, Methodology, Data curation, Writing – original draft. **Gauti Asbjörnsson**: Conceptualization, Investigation, supervision, Writing – review & editing, Funding acquisition. **Francisco Ortega**: Data curation, Writing – review & editing. **Noemi Ariza-Rodríguez**: Data curation, Writing – review & editing. **Diego Mesa**: Data curation, Writing – review and editing. **Pablo R. Brito-Parada**: Writing – review & editing. **Magnus Evertsson**: Writing – review & editing, Funding acquisition.

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Appendix A. Allocation

The first level of allocation has been performed based on the consumption of each resource in different operations.

The following describes the allocation of each resource and waste.

- Diesel: The total quantity of diesel consumed was allocated based on machine-specific usage as follows:

  (a) Diesel used by excavators during the extraction process was allocated to ore extraction.
  (b) Diesel consumed by trucks and wheel loaders was allocated to transportation,
  (c) Diesel consumed by the mobile crusher, screen, and powering the equipment at the pilot plant was allocated to the production process.

- Electricity is consumed only during the tailings enrichment and in offices. Hence, all the electricity consumed at the site is allocated to the production process.
- Explosives are only used during blasting and hence allocated to ore extraction.
- Water is consumed during site preparation and the tailings enrichment process. It is allocated as follows

  (a) Water consumed during site preparation was allocated to ore extraction.
  (b) Water consumed at the pilot plant during the enrichment process was allocated to the production process.

- Lubricants – the total quantity of lubricants consumed was allocated based on machine-specific usage, similar to diesel.
- Metal consumption was documented based on spare parts needed to repair the mobile crusher, screen, and equipment at the pilot plant. Hence, the total quantity of metals consumed is allocated to the production process.
- FeSi is only consumed at the pilot plant. Hence, the total quantity of FeSi consumed is allocated to the production of +1 -6 mm celestine.
- Chemical consumption refers to the addition of chemicals to diesel. Hence, an allocation similar to that of diesel is used.
- Plastic consumption occurs only due to packaging. Hence, it is only allocated to the production process.
- Rubber was allocated by assuming the same partitioning as diesel.

Appendix B. Data estimation

The following describes the data estimation concerning the production quantity, resource consumption, and waste for scenarios 2, 3, and 4.

Scenario 2

Scenario 2 was developed based on the site's capability to tailor the processing circuit to obtain celestine with different size fractions. Since scenario 2 processes only medium-grade ore, the production quantity, resource consumption, and waste data were estimated based on scenario 1 (case b).

- The production quantity was estimated as follows,

$$P_2 = \frac{P_{1b}}{RoM_{1b}} * RoM_2$$

Where, P_2 is the estimated production quantity of celestine in scenario 2, P_{1b} is the production quantity of celestine in scenario 1 (case b), RoM_{1b} is the total quantity of RoM ore processed in scenario 1 (case b), and $RoM_2$is the total quantity of RoM ore processed in scenario 2.

- The data for resources consumed and waste generated was estimated by utilizing the following formula,

$$A_2 = \frac{A_{1b}}{RoM_{1b}} * RoM_2$$

Where, A_2 is the estimated quantity of resources consumed or waste generated in scenario 2 and A_{1b} is the quantity of resources consumed or waste generated in scenario 1 (case b).

- The data for diesel and lubricant were estimated by utilizing the following formula

$$A_3 = (\frac{A_{1b}}{RoM_{1b}} * RoM_2) - Z$$

Where, A_3 is the estimated quantity of diesel or lubricant consumed in scenario 2, A_{1b} is the diesel or lubricant consumed in scenario 1 (case b), and Z is the quantity of diesel (1,000 liters) or lubricant (134 liters) that needs to be subtracted, since the crushing bucket requires a lower quantity of diesel because it processes a lower quantity of material in scenario 2 compared to scenario 1 (case b).

Scenario 3 and 4

The data concerning the production quantity, resource consumption, and waste data for scenarios 3 and 4 were estimated based on scenarios 1 (case b) and 2, respectively. The following describes the estimation model,

- The production quantity was estimated as follows,

$$P_X = (\frac{P_Y}{RoM_Y} * RoM_X) + P_E$$

Where P_X is the estimated production quantity of celestine produced in scenario 3 or 4, P_Y is the production quantity of celestine in scenario 1 (case b) or scenario 2, RoM_Y is the total quantity of RoM ore processed in scenario 1 (case b) or scenario 2, RoM_X is the total quantity of RoM ore processed in scenario 3 or 4, and P_E is the quantity of +1 –6 mm celestine produced from the tailings enrichment process.

Resource consumption and waste data were estimated as follows

- Diesel consumption was estimated as follows,

$$D_X = \left(\frac{D_Y}{RoM_Y} * RoM_X\right) + D_E$$

$$D_E = D_{DS} + D_{DMS}$$

Where D_X is the total quantity of diesel consumed in scenario 3 or 4, D_Y is the quantity of diesel consumed in scenario 1 (case b) or 2, D_E is the total quantity of diesel consumed during the tailings enrichment process, D_{DS} is the diesel consumption during the desliming process, and D_{DMS} is the diesel consumption during the DMS.

- Electricity consumption in scenario 3 was estimated as follows

$$E_X = \left(\frac{E_Y}{RoM_Y} * RoM_X\right) + E_E$$

Where, E_X is the estimated quantity of electricity consumed in scenarios 3 and/or 4, E_Y is the total quantity of electricity consumed in scenario 1 (case b) and/or 2, E_E is the total quantity of electricity consumed during the tailings enrichment process.

- Water consumption during the tailings enrichment process was estimated by assuming that 30% of the pulp entering the hydrocyclone was solids (i.e. tailings and FeSi). In addition, since the enrichment is a closed circuit, a water recycling rate has been considered during the estimation. The following presents the formula used for the estimation,

Table B1. Estimation of diesel consumption.

Pilot plant	Yearly operating hours	Hourly diesel consumption (liters per hour)	Annual diesel consumption (liters per year)
D_{DS}	750	10	7,500
D_{DMS}	1,050	15	15,750

$$W_X = \left(\frac{W_Y}{RoM_Y} * RoM_X\right) + [(Q/pct) * (1 - R_W)]$$

Where, W_X is the estimated quantity of water consumed in scenario 3 or 4, W_Y is the quantity of water consumed in scenario 1 (case b) or 2, Q is the quantity of solids entering the hydrocyclone, pct is the percentage of solids entering the hydrocyclone and R_W is the recycling rate of water (see Table B2)

- In the case of FeSi, the data was estimated based on the laboratory tests carried out by Ariza-Rodríguez et al. (2023).
- Other consumables such as rubber, lubricants, chemicals,

$$A_X = \left(\frac{A_Y}{RoM_Y} * RoM_X\right) * (1 + SF) \tag{8}$$

Where, A_X is the estimated quantity of resource consumed or waste generated in scenario 2, A_Y is the production quantity in scenario 1 (case b), and SF is the scaling factor.

Table B2. Parameters used for the data estimation.

Parameter	Values	Unit
Scaling factor, *SF*	12	%
The total quantity of solid material entering the hydrocyclone, *Q*	31,138	tonne
Percentage of solids entering the hydrocyclone, *pct*	30	%
Water recycling rate, R_W	90	%

Appendix C: LCI data sets

Table C1. Description of LCI data sets used for modeling the resource consumption and waste.

Data	Data set description
Diesel	This dataset covers the production and combustion of one liter of diesel for the EU-28 geography.
Energy	This data set includes the grid mix for Spain.
Water	This dataset includes all relevant process steps (e.g. Filtering, sedimentation, flocculation, decarbonization, disinfection, and chlorination) to produce tap water for the EU-28 region.
Oil	This dataset includes the production of lubricants at the refinery for the EU-28 geography.
Metal	This data set includes the raw material extraction and production of steel hot rolled coil based on Worldsteel data 2018, covering the EU geography.
FeSi	Proxy dataset: This includes the production of steel hot rolled coil based on Worldsteel data 2018, covering the EU geography.
Rubber	This includes the production of Styrene-Butadiene Rubber (SBR). The dataset covers the EU geography.
Chemicals	This includes the production of inorganic chemicals based on ecoinvent 3.6 for the global geography. The dataset covers the EU geography.
Explosives	This dataset includes the manufacturing of explosives, transport to a 300-kilometer site, consumption, and use of a custom detonator wire based on the specification of an Orica detonator wire. The dataset covers the EU geography.
Mixed waste*	This includes the dataset for the waste treatment at the waste incineration plant for the EU-28 geography.
Hazardous waste*	This includes the dataset for the hazardous waste treatment at the waste incineration plant for the EU-28 geography.
Inert Rock waste	This dataset is modeled as non – hazardous waste, which requires no additional treatment and is stored at the mining site.

**All waste treatment processes include 150 kilometers of transport as a standard distance between the site and the waste-handling facility.*

Appendix D: Models in Environmental Footprints (EF) 3.0 quantifying the impact categories

Table D1. Models in environmental footprints (EF) 3.0.

Impact category	Unit	Model
Global warming potential total, GWP – total	kg CO_2 eq.	IPCC baseline, 100 years, 2013
Depletion potential of the stratospheric ozone layer, ODP	kg CFC-11 eq.	Steady-state ODPs, WMO 2014
Acidification potential, Accumulated Exceedance, AP	Mol H^+ eq.	Accumulated Exceedance, Seppälä et al. 2006, Posch et al. (2008)
Eutrophication potential, fraction of nutrients reaching freshwater end compartment, EP-freshwater	Kg P eq.	EUTREND model, Struijs et al. (2009), as implemented in ReCiPe
Formation potential of tropospheric ozone, POCP	kg NMVOC eq.	LOTOS-EUROS, Van Zelm et al., 2008, as applied in ReCiPe
Abiotic depletion potential for fossil resources, ADP-fossil fuels	MJ, net calorific value	CML 2002, Van Oers et al. (2002)

*IPCC – Intergovernmental Panel on Climate Change.
*WMO – World Meteorological Organization.

Appendix E: Consumption of different resources and waste for producing 1 tonne of celestine

Table E1. Consumption of resources and waste per tonne of celestine.

	Scenario 1		Scenario 2		Scenario 3		Scenario 4		
Resources and waste	Case a <35 mm	Case b <35 mm	<35 mm	+6 –20 mm	<35 mm	+1 –6 mm	<35 mm	+6 –20 mm	+1 –6 mm
Diesel	3.5E–01	3.6E–01	3.5E–01	3.5E–01	3.8E–01	8.8E–01	3.5E–01	3.5E–01	8.6E–01
Electricity	1.1E–01	1.1E–01	1.1E–01	1.1E–01	9.6E–02	8.8E–01	1.0E–01	1.0E–01	8.8E–01
Water	1.4E–02	1.4E–02	1.4E–02	1.4E–02	1.2E–02	4.9E–01	1.2E–02	1.2E–02	4.9E–01
Lubricants	1.1E–02	1.5E–02	1.4E–02	1.4E–02	1.4E–02	1.5E–02	1.4E–02	1.4E–02	1.4E–02
Metal	4.0E–02	4.0E–02	4.0E–02	4.0E–02	4.0E–02	4.0E–02	4.0E–02	4.0E–02	4.0E–02
Ferro silicon	0.0E + 00	0.0E + 00	0.0E + 00	0.0E + 00	0.0E + 00	3.0E + 00	0.0E + 00	0.0E + 00	3.0E + 00
Rubber	6.8E–04	6.9E–04	6.9E–04	6.9E–04	6.9E–04	6.9E–04	6.9E–04	6.9E–04	6.9E–04
Plastic	5.5E–04	5.5E–04	5.5E–04	5.5E–04	5.6E–04	5.6E–04	5.6E–04	5.5E–04	5.6E–04
Chemicals	1.1E–03	1.1E–03	1.1E–03	1.1E–03	1.1E–03	1.1E–03	1.1E–03	1.1E–03	1.1E–03
Explosives	5.5E–02	5.5E–02	5.6E–02	5.5E–02	5.0E–02	5.0E–02	5.0E–02	5.0E–02	5.0E–02
Mixed waste	3.8E–03	3.8E–03	3.8E–03	3.8E–03	3.8E–03	3.8E–03	3.8E–03	3.8E–03	3.8E–03
Hazardous waste	6.1E–03	6.1E–03	6.1E–03	6.1E–03	6.1E–03	6.1E–03	6.1E–03	6.1E–03	6.1E–03
Inert Rock waste	1.4E–04	2.5E–01	2.5E–01	2.5E–01	1.1E–01	1.1E–01	1.1E–01	1.1E–01	1.1E–01

Appendix F: Results for impact categories

The following table presents the cradle-to-gate LCA results for the impact categories assessed in this study.

Table F1. Absolute values for the environmental impact of different products.

Impact categories	Operations	S1a (<35 mm – HG)	S1b (<35 mm – MG)	S2 (<35 mm – MG)	S2 (+6 –20 mm – MG)	S3 (<35 mm – MG)	S3 (+1 –6 mm – MG)	S4 (<35 mm – MG)	S4 (+6 –20 mm – MG)	S4 (+1 –6 mm – MG)
GWP-total (kgCO$_2$-eq./tonne)	Ore extraction	3.9E–01	3.9E–01	3.8E–01	3.8E–01	3.5E–01	3.5E–01	3.5E–01	3.5E–01	3.5E–01
	Ore transportation	7.1E–01	7.1E–01	6.8E–01	6.8E–01	6.9E–01	8.2E–01	6.5E–01	6.5E–01	8.2E–01
	Production process	2.1E–01	2.3E–01	2.3E–01	2.3E–01	2.3E–01	8.5E+00	2.2E–01	2.1E–01	8.4E+00
POCP (kg NMVOC eq./tonne)	Ore extraction	2.4E–03	2.4E–03	2.4E–03	2.4E–03	2.2E–03	2.2E–03	2.2E–03	2.2E–03	2.2E–03
	Ore transportation	3.8E–03	3.8E–03	3.7E–03	3.7E–03	3.8E–03	4.4E–03	3.7E–03	3.7E–03	4.4E–03
	Production process	6.3E–04	7.8E–04	7.5E–04	7.5E–04	7.2E–04	2.2E–02	7.1E–04	6.6E–04	2.2E–02
AP (Mol H$^+$ eq./tonne)	Ore extraction	2.7E–03	2.7E–03	2.6E–03	2.6E–03	2.4E–03	2.4E–03	2.4E–03	2.4E–03	2.4E–03
	Ore transportation	4.1E–03	4.1E–03	3.9E–03	3.9E–03	4.1E–03	4.7E–03	3.9E–03	3.9E–03	4.7E–03
	Production process	7.6E–04	9.2E–04	8.8E–04	8.8E–04	8.6E–04	2.8E–02	8.5E–04	7.9E–04	2.8E–02
EP (kg P eq./tonne)	Ore extraction	1.1E–06	9.6E–07	1.1E–06	1.1E–06	1.0E–06	1.0E–06	1.0E–06	1.0E–06	1.0E–06
	Ore transportation	2.1E–06	2.1E–06	2.0E–06	2.0E–06	2.1E–06	2.4E–06	2.0E–06	2.0E–06	2.4E–06
	Production process	1.1E–06	1.3E–06	1.1E–06	1.1E–06	1.1E–06	1.5E–05	1.1E–06	1.1E–06	1.4E–05
ADP fossil (MJ, net calorific value/tonne)	Ore extraction	5.2E+00	5.2E+00	5.1E+00	5.1E+00	4.7E+00	4.7E+00	4.7E+00	4.7E+00	4.7E+00
	Ore transportation	9.7E+00	9.7E+00	9.4E+00	9.4E+00	9.7E+00	1.1E+01	9.4E+00	9.4E+00	1.1E+01
	Production process	2.6E+00	3.1E+00	2.9E+00	2.9E+00	2.9E+00	8.9E+01	2.8E+00	2.7E+00	8.8E+01