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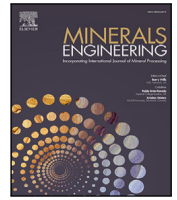
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Strontium minerals as critical raw materials — Market dynamics, processing techniques, and future challenges

Diego Mesa [a,*], Varun Gowda [b], Francisco Ortega [c,d], Kanishk Bhadani [b], Noemi Ariza-Rodríguez [c,d], Gauti Asbjörnsson [b], Pablo R. Brito-Parada [a]

[a] *Advanced Mineral Processing Research Group, Department of Earth Science and Engineering, Imperial College London, London, United Kingdom*
[b] *Department of Industrial and Materials Science, Division of Product Development, Chalmers University of Technology, Gothenburg, Sweden*
[c] *Canteras Industriales S.L., Montevive, Granada, Spain*
[d] *Chemical Engineering Department, Faculty of Science, University of Granada, Granada, Spain*

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ABSTRACT

In 2020, the European Union officially designated strontium as a Critical Raw Material (CRM) due to its diverse applications and limited global producers, with Spain as one of the primary producers and the only one in the EU. This comprehensive review discusses strontium market dynamics, global reserves, and technological advancements in mineral processing techniques to extract and concentrate its main bearing minerals, celestine ($SrSO_4$) and strontianite ($SrCO_3$). The review highlights the shift in strontium demand, led until the mid-2000s by applications in cathode-ray tube (CRT) glass, to current uses focused on pyrotechnics, ceramic magnets and drilling fluids.

The study evaluates the progression of beneficiation methods, from manual sorting to advanced techniques such as size separation, gravity separation, flotation, and dense media separation, with recent innovations demonstrating enhanced recovery and purity of celestine concentrates. Industrial case studies from various regions, including Spain and China, illustrate significant advances and regional variations in celestine processing, while emphasising the need for further research and transparency in reporting beneficiation methodologies.

Furthermore, the review addresses the gaps and unavailability of environmental impact assessment of strontium production and underscores the importance of improving circularity through recycling, particularly in light of the negligible End-of-Life Recycling Input Rate (EOLRIR) for strontium in the EU. Emerging applications in magnet technology, medicine, and smart materials present new opportunities, potentially reducing reliance on rare-earth elements and fostering innovation.

The paper also explores the anticipated effects of the CRM status of strontium on future demand, highlighting the need for continued research and technological advances in strontium beneficiation to ensure a stable supply chain. The sustained study and optimisation of extraction and processing methodologies are crucial in meeting the demand from evolving industrial applications and addressing current and future challenges in the supply of this CRM.

Contents

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* Corresponding author.
  E-mail address: d.mesa@imperial.ac.uk (D. Mesa).

1. Introduction

Strontium, identified by the symbol Sr and atomic number 38, is an alkaline earth metal classified as a Critical Raw Material (CRM) by the European Union since 2020 (European Commission, 2020b, 2023), as well as by Japan and South Korea (Agency for Natural Resources and Energy of Japan, 2020; Lee and Cha, 2021). Strontium is a commonly occurring element, being the 15th most abundant element on Earth's crust. Its physical and chemical attributes (see Table 1) closely resemble those of its neighbouring elements in the periodic table, calcium and barium (MacMillan et al., 2000).

Strontium is a highly reactive element. Consequently, it is never found in its pure state due to its rapid oxidation upon exposure to air, leading to the formation of diverse minerals. The most common strontium-bearing mineral and the principal source of strontium through mining is celestine ($SrSO_4$), distantly followed by strontianite ($SrCO_3$). More details about the strontium-bearing minerals and their properties are detailed in the following section.

The primary use for strontium in previous decades was to produce a special glass for colour television cathode-ray tubes (CRTs) capable of preventing the emission of harmful X-rays. However, with the rapid advancements in flat-panel technologies for television and computer screens, CRTs have become obsolete, resulting in a declining demand for strontium carbonate in this sector. Nevertheless, strontium is still utilised in the glass industry to improve the optical and mechanical properties of materials, enhance transparency, increase refractive index, and reduce chromatic aberration in optical lenses (Ramzi et al., 2016; Dirección General de Desarrollo Minero, 2021, 2022; Bouabdalli et al., 2023; Kavgacı et al., 2024).

Nowadays, the main use of strontium compounds is in pyrotechnics, drilling fluids and ceramic magnets (European Commission, 2023; USGS, 2023). In pyrotechnics, strontium is used for the brilliant reds in fireworks and warning flares and in some 'glow-in-the-dark' paints and plastics. In the case of drilling fluids, strontium sulphate and strontium carbonate are utilised as additives to enhance drilling performance in the oil and gas sector, preventing the formation of scales, such as calcium carbonate and barium sulphate. Finally, strontium ferrite magnets ($SrFe_{12}O_{19}$) are commonly used in small motors, loudspeakers, electronics, and toys due to their favourable magnetic properties and low cost (Kanagesan et al., 2013; Harris, 2023). Other uses of strontium include medicine, where strontium compounds such as strontium ranelate ($C_{12}H_6N_2O_8SSr_2$) have been used for their potential to increase bone density and reduce the risk of fractures in postmenopausal women with osteoporosis (Reginster et al., 2005; Li et al., 2019; Mukherjee and Mishra, 2021).

Table 1
Properties of strontium (Sr).

Atomic number	38
Atomic mass	87.62 g/mol
Specific gravity	2.64
Melting point	1050 K
Boiling point	1650 K
Number of isotopes	14
Pauling electronegativity	0.95
Appearance	Soft, silver-yellowish metal
Other properties	Strontium metal powder spontaneously ignites in the air. Strontium volatile salts impart a bright red colour to flames.

1.1. Strontium-bearing minerals

Strontium is found in various minerals, notably celestine (strontium sulphate, $SrSO_4$ - also known as celestite), strontianite (strontium carbonate, $SrCO_3$), strontium fluoride (SrF_2), strontium molybdate ($SrMoO_4$), and strontium titanate ($SrTiO_3$). These minerals are commonly located in diverse geological formations, including sedimentary, igneous, and metamorphic rocks.

Celestine stands out as the most abundant and significant source of commercial strontium. However, despite celestine being a relatively common mineral in sedimentary environments, large economically exploitable deposits are rare. Strontianite is the second most abundant strontium mineral, yet considerably less common than celestine. Strontianite mineral is much more convenient to extract as it is closer to the most common commercial strontium product, strontium carbonate ($SrCO_3$), however, only a few economic deposits of strontianite have been discovered, including the old strontianite mine in the village of Strontian in Argyll, Scotland, from which the element obtained its name (Livingstone et al., 2022; National Museums Scotland, 2024), and a deposit in Sierra Mojada, Mexico (Krieger, 1933; Dirección General de Desarrollo Minero, 2021, 2022). Although less common, strontium fluoride, strontium molybdate, and strontium titanate (SrF_2, $SrMoO_4$, and $SrTiO_3$, respectively) can be exploited for industrial applications.

Despite strontium's relative abundance, significant reserves are confined to a handful of countries. Global strontium reserves exceed one billion tons distributed between China, Iran, Spain, the United States, Mexico, and Argentina (Nesse, 2017; USGS, 2024). The latest survey from USGS (2024) estimates reserves of 12 million tonnes of strontium in China and 7.1 million tonnes in Iran, as depicted in Fig. 1. In Spain, the Geological and Mining Institute (IGME) estimated a decade ago that the *Depresión de Granada* area held around 12 million tonnes of celestine reserves (IGME, 2024). Although no up-to-date official estimations are publicly available for Spain, Minas de Escúzar has recently reported reserves of about 1 million tonnes (IGME, 2024), while Canteras Industriales has reported to the press reserves of 4 million tonnes (La Razón, 2023; La Voz del Sur, 2023). A recent review by Rosa et al. (2023) reports over 9 million tonnes of strontium reserves
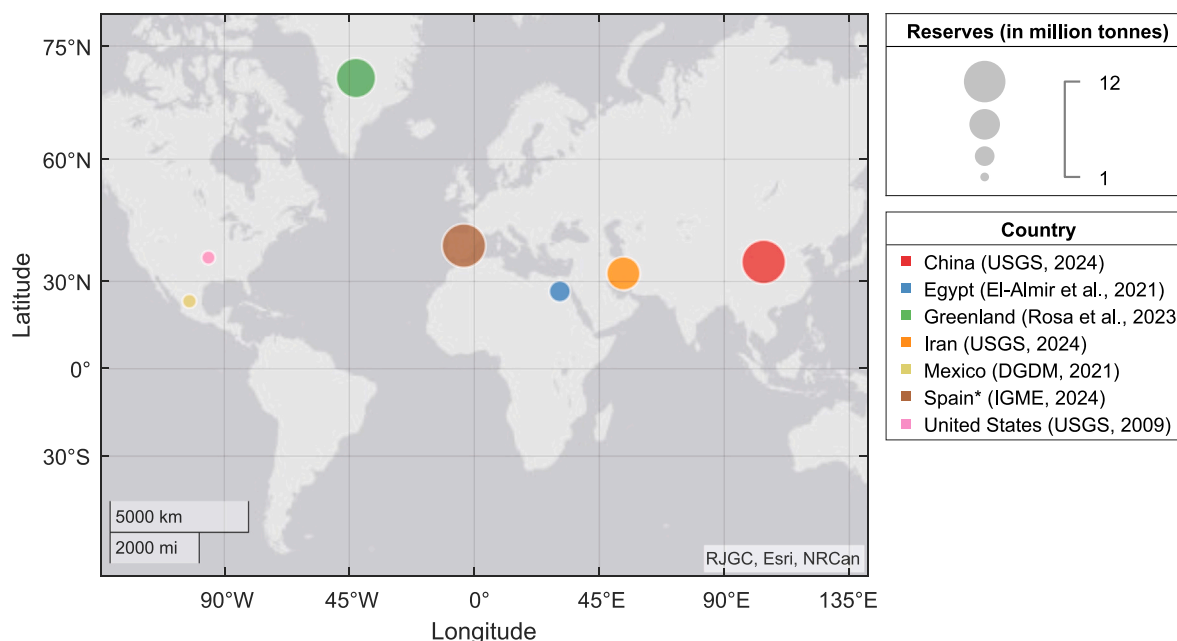
Fig. 1. Global reserves of strontium ore, in millions of tonnes. Data from USGS (2009, 2024), Dirección General de Desarrollo Minero (2021, 2022), El-Amir et al. (2021), Rosa et al. (2023) and IGME (2024). Estimated world reserves exceed 1 billion tonnes. (*) Spanish estimated reserves of 12 million tonnes are over two decades old, yet no up-to-date estimates are available.

in Greenland, yet no exploitation activity is known in the area. A similar case occurs in Egypt, where reserves strontium reserves have been estimated on approximately 3 million tonnes (El-Amir et al., 2021). Among these countries, Iran, Spain, China, and Mexico have been major producers, while the United States, although possessing substantial reserves, has not commercially mined strontium since 1959 (USGS, 2022).

1.2. Market dynamics

The dynamics of the strontium market have undergone significant transformations, shaped by shifts in global production patterns and technological advancements. As depicted in Fig. 2, the global production of strontium exhibited a nearly linear growth from the 1970s through the 1990s. Subsequently, from the 1990s to the early 2000s, production accelerated even further, peaking around 2005 at an annual output exceeding 500,000 tonnes. However, a pronounced downturn in the late 2000s led to production levels stabilising between 300,000 and 400,000 tonnes per year until 2020. Notably, a recent surge has brought production levels back to the historical peak of 500,000 tonnes in the last three years.

The changes in global production observed in Fig. 2 can be associated, among other variables, with shifts in the production share by different countries. Fig. 3 shows the estimated global production of celestine per country, based on USGS reports from 1998 to 2023 (USGS, 2009, 2020, 2022, 2023, 2024). It can be observed that by the end of the 20th century, Mexico led the global production of celestine, followed by Spain. Mexico's share of the global market quickly decreased in the following years, being replaced by China, which by the year 2010 dominated global production with almost 200,000 tonnes per year. Chinese production, however, commenced a steep decrease after 2012, accompanied by the irruption of Iran as a new global competitor. Notably, Spain has remained an important global producer of celestine for the last 25 years.

According to the most recent report by the European Union (European Commission, 2023), Iran holds the dominant position in global strontium production, commanding a market share of 37%, closely trailed by Spain at 34% and China at 16%. Although figures may
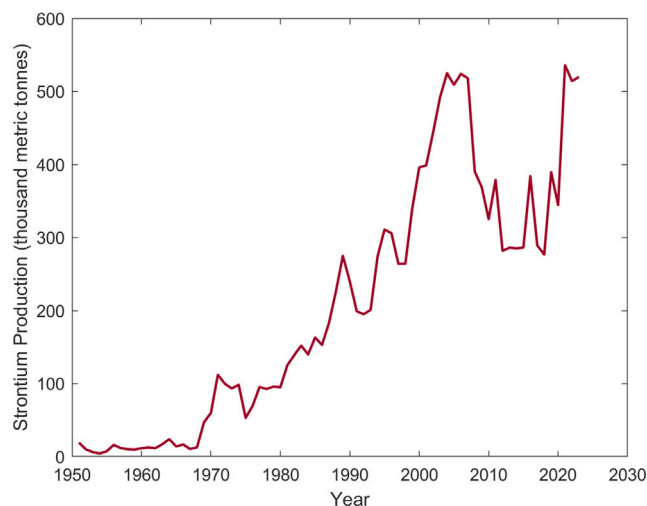

Fig. 2. Annual world production of strontium in thousand tonnes, depicting the growth of Sr production since the 1970s associated with its use in cathodic ray tube (CRT) televisions, achieving a peak in the mid-2000s, followed by a sharp decay in production due to the replacement of CRTs by LCD technology, and the return to historic-high production levels in the last couple of years, associated to its recognition as a critical raw material for the production of ceramic magnets and pyrotechnics.
Source: Data from USGS (2020, 2023, 2024).

slightly diverge in the latest USGS report (USGS, 2024), which depicts Spain and Iran as equal contenders with a production of 200,000 tonnes each in 2023, followed by China at 80,000 tonnes, the overarching trend highlights the importance of these three nations in the current strontium production. Furthermore, Spain maintains its status as the primary strontium supplier to the EU, furnishing 99% of the supply, thereby ensuring the EU's minimal import reliance (European Commission, 2023).

The marked shifts in the global production observed in Figs. 2 and 3 can be explained by drastic changes in the end-use distribution of strontium, illustrated in Fig. 4 for the period from 1975 to the mid-2000s. Strontium's primary application during that period was in
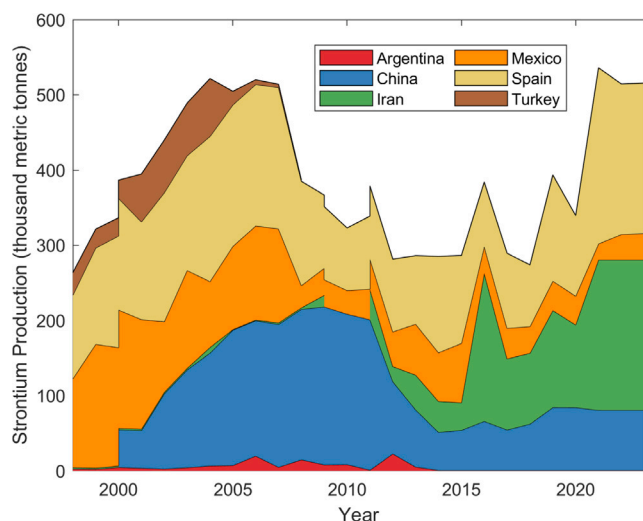
Fig. 3. Annual production of strontium ore by countries, in thousand tonnes. *Source:* Data from USGS (2020, 2023, 2024).
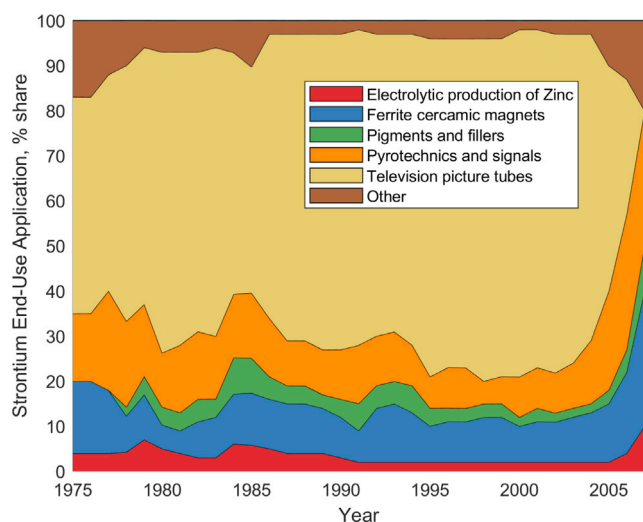

Fig. 4. Historic estimated end-use distribution of Strontium between 1975 and 2007. The figure shows the abrupt fall in the use of strontium for television cathodic tubes in the mid-2000s. Data from USGS reports until 2007. USGS stopped reporting the end-use distribution after 2008.

the faceplate glass of CRTs for televisions and monitors, as strontium prevented X-ray emission (Andreola et al., 2007; Engelsen, 2008; USGS, 2020). In the year 2000, 77% of the strontium consumption was used for CRTs, particularly in the production of Shadow Mask CRTs used in the Colour Display Tube (CDT). The growth of the production of Shadow Mask CRTs was also motivated by the disruptive need for monitors for Personal Computers (PCs). However, the advent of Liquid Crystal Display (LCD) led to a rapid decline in demand for CRTs within a couple of years (Engelsen, 2008), marking a pivotal shift in strontium consumption dynamics. The change in display technology from CRTs to LCD strongly correlates with the production dynamics observed in Figs. 2 and 3.

The stabilisation of global production in the last decades can be attributed to the expansion and diversification of strontium applications and their markets. Fig. 5 shows the estimated share of strontium in different end-use applications in the European Union and the United States for the 2022–2023 period, based on reports by the European Commission (European Commission, 2023) and USGS (USGS, 2023). Strontium compounds were majorly used in drilling fluids in the United
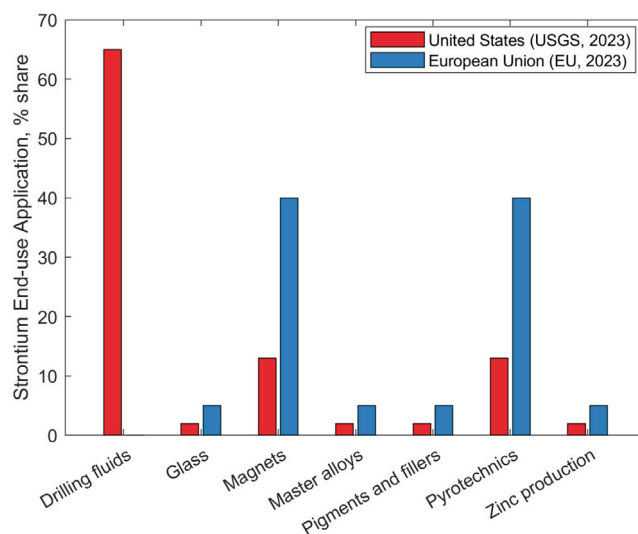

Fig. 5. Estimated end-use distribution of strontium nowadays in the United States and the European Union. *Source:* Data from USGS (2023) and European Commission (2023).

States (65%) and minimally in the European Union (less than 1%). The European Union reported higher shares in applications like magnets and pyrotechnics (40% each) compared to the United States (13% each). Additional small shares were distributed across applications such as aluminium-strontium master alloys (Sezer et al., 2020), removal of lead during electrolytic zinc production (Bratt and Smith, 1965; Sinclair, 2005), and production of blue, yellow and photochromic pigments (Jose and Reddy, 2013; Zhang et al., 2016; Otero et al., 2017; Khattab et al., 2018).

The strontium market has grown in recent years. Different market research companies have valued the global market at USD 200–300 million in 2023, with a compound annual growth rate (CAGR) of 4%–6% (Market Research Future, 2024; Verified Market Research, 2024; Skyquest, 2024; Grand View Research, 2024). Production has increased, reaching similar values as during the peak in the mid-2000s (see Fig. 2). This rapid growth impacted the price of strontium, especially in 2021 (see Fig. 6). Strontium is not listed on futures exchanges such as the London Metal Exchange (LME) or the New York Mercantile Exchange (NYMEX). Instead, the price is negotiated between private companies. Thus, it is not simple to define a single price for strontium. Moreover, strontium is not commercialised as a pure metal but mainly as celestine concentrate or as strontium carbonate, among other commercial products.

The USGS has established a procedure to estimate the unit value of strontium (USGS, 2023). The unit value is defined as the value of 1 metric ton (t) of apparent strontium consumption in the US. Unit value data were estimated by taking the total value of strontium imports, which include strontium carbonate, chromate, metal, minerals, nitrate, salts, sulphate, and other unspecified compounds, and dividing it by the total tonnage of strontium contained in these imports. Fluctuations in the unit value series may not necessarily reflect changes in actual value but rather variations in the type, quantity, and quality of the strontium imports. These unit values can be adjusted to a defined base year real value using the Consumer Price Index conversion factor. USGS has used 1998 as the base year in order to allow for comparisons. The equivalent unit values for strontium between 1970 and 2022, based on the 1998-dollar value, are shown in Fig. 6.

Historically, strontium value has fluctuated between 400 and 800 USD$_{98}$/ton (USD base 1998). During the production crisis after 2010, the value of strontium fell near 300 USD$_{98}$/ton. The highest unit value of strontium recorded by the USGS was in 2021, reaching 1390 USD$_{98}$/ton (2310 USD/ton in nominal value). The price in 2022 fell but is still higher than the historical average.
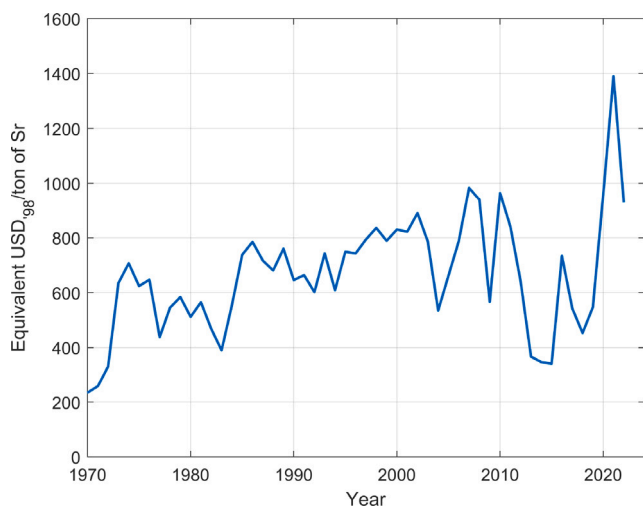
Fig. 6. Equivalent unit value of strontium, in US dollars per metric tonne. The values were converted using the Consumer Price Index, with 1998 as the base year, for comparison.
Source: Data from USGS (2023).

1.3. Strontium – a Critical Raw Material

The European Commission published the first Critical Raw Materials list in 2011. This first list consisted of 14 raw materials considered essential for the advancement of key emerging technologies in Europe, such as battery technology, solar panels, permanent magnets, and other clean technologies (Massari and Ruberti, 2013). Since then, the list of CRMs in the European Union has been updated at three-year intervals in 2014, 2017, 2020, and 2023. Several other countries have published their own lists of critical minerals since then, including the United States (U.S. Department of Energy, 2023), the United Kingdom (Lusty et al., 2021; Josso et al., 2023), Japan (Agency for Natural Resources and Energy of Japan, 2020; Nakano, 2021), Canada (International Energy Agency, 2022a; Government of Canada, 2023), South Korea (International Energy Agency, 2023a), Australia (International Energy Agency, 2024; Department of Industry Science and Resources of Australia, 2024), India (Gupta et al., 2016; International Energy Agency, 2023b; Committee on Identification of Critical Minerals of India, 2023) and China (International Energy Agency, 2022b), among others.

The list of CRMs of the European Union is created based on two main parameters, *i.e.*, Supply Risks (SR) and Economic Importance (EI) of the raw material for the whole European Union's economy. The SR parameter assesses the potential risk of a disruption in the supply of the material within the European Union (Commission, 2017). The EI parameter provides insights into the significance of a material to the European Union economy, considering its utilisation in end-use applications and the value it adds to the relevant manufacturing sectors within the EU. The thresholds for the parameter remain at $SR \geq 1.0$ and $EI \geq 2.8$, and any raw material which reaches or exceeds these thresholds is categorised as a CRM.

Strontium was recognised as a CRM for the first time in 2016 by India (Gupta et al., 2016), followed by the United States in 2018 (U.S. Department of Interior, 2018), and Japan in 2019 (Agency for Natural Resources and Energy of Japan, 2020; Nakano, 2021), while the European Union (European Commission, 2020a) and South Korea (Lee and Cha, 2021) added strontium into their critical metals lists in 2020. The latest report by the European Union for 2023 consists of 32 CRMs, among which strontium remains included, with an EI of 2.6 and an SR of 6.5. The creation of these lists has incentivised investment into the production of CRMs both within the European Union and abroad (European Commission, 2023).

In 2024, the EU, Japan and South Korea continue to designate strontium as a CRM, while the United States has diverged from this policy, as documented by USGS, Department of the Interior (2022). Strontium was also removed from India's last list of critical minerals, yet the Committee on Identification of Critical Minerals of India (2023) recommends its reincorporation.

In the case of the US, this shift primarily stems from strontium failing to meet the quantitative threshold and lacking a single point of failure. Notably, in the United States, the strontium market falls just below the quantitative threshold for SR scoring. This underscores the understanding that the metrics derived from the different methodologies to define the criticality of raw materials represent a spectrum of supply risks rather than an indication that commodities below the quantitative cutoff are devoid of supply risk (USGS, Department of the Interior, 2021). In essence, the analysis reveals that while strontium exhibits a significant trade exposure, its potential for disruption is relatively low. This finding underscores the reality that, although the United States heavily relies on net imports of strontium, the mineral's production is dispersed across nations deemed dependable trade partners, mitigating the risk associated with concentration in a single source.

2. Beneficiation of strontium minerals

The beneficiation of strontium-bearing ores in mineral processing relies on various techniques, tailored to the specific properties of each ore deposit. Celestine, the most common strontium mineral, is processed to obtain a >90% rich concentrate of $SrSO_4$. This celestine concentrate can be directly commercialised or continue its enrichment process to convert it into strontium carbonate ($SrCO_3$), one of the most common commercial forms of strontium. This conversion stage is reviewed in Section 3.

Most celestine operations have historically exploited coarse-rich ores that could be enriched by hand picking, achieving grades over 90% of $SrSO_4$ (Ariza-Rodríguez et al., 2022; MacMillan et al., 2000). Typically, these manual operations commence with overburden removal, followed by shallow pit excavation for ore extraction. Subsequently, the Run of Mine (RoM) ore undergoes crushing and sizing, followed by hand-picking based on colour, size, and weight criteria (Ariza-Rodríguez et al., 2022; Bulatovic, 2015; Castillejos et al., 1996).

Nowadays, several other mineral processing techniques are used to separate the celestine from the associated gangue minerals. The most common gangue ores discussed in the literature are calcite (El-Midany and Ibrahim, 2011; El-Midany et al., 2011), limonite and clays (Bulatovic, 2015) such as illite and kaolinite. Other gangue minerals include quartz and iron oxides (Ariza-Rodríguez et al., 2022). The primary objective of the beneficiation process remains the attainment of a celestine concentrate with a requisite grade, typically exceeding 90% $SrSO_4$ (Castillejos et al., 1996; Selim et al., 2010).

2.1. Concentration by size separation

Ariza-Rodríguez et al. (2022) demonstrated that low to medium-grade celestine mineral (about 60% celestine), which used to be considered uneconomical in hand-sorting operations and accumulated in dumps and mine tailings, can be concentrated through grinding and size separation. The coarser fractions (>5 mm) have a greater concentration of celestine (up to 12 percent units more) due to the selective loss of calcite and other minerals (quartz, clays, and iron oxides). This process, however, cannot be applied to high-grade minerals (about 90% celestine) as there is no additional increase in the concentration of celestine, and separation enhancements would be uneconomical.

In another study, however, El-Midany et al. (2011) highlighted the limitations in separating celestine from calcite using attrition scrubbing, a method that is essentially based on size separation and is widely

used for soil washing. Based on the difference in the hardness and friability between celestine and calcite, the authors expected calcite to be collected in the fine fraction. However, their results showed that calcite was present both in the fine and coarse fractions due to interlocking, lack of liberation at coarser sizes, and therefore required fine grinding.

2.2. Gravity separation

Gravity separation is another concentration technique widely used in celestine beneficiation. Selim et al. (2010) studied the use of jigs for coarse size ($+2\,mm\ -15\,mm$) celestine concentration and shaking tables for finer size concentration ($+80\,\mu m\ -500\,\mu m$). In their work, the authors used the jig to obtain a pre-concentrate of coarse celestine, with up to 55% celestine content. The operation of the shaking table to concentrate the fine fraction was optimised using a 2^4 full factorial design, varying water flow rate, feed pulp density, table slope and stroke length. Response surfaces showed that the shaking table slope was the most effective factor, resulting in higher concentrate grades and recoveries at higher slopes, although the authors only tested up to a 6° slope. Gravity separation using jigs and tables can also be used as a pre-concentration method before moving to other techniques such as flotation (Bulatovic, 2015).

Recently, Sobhy et al. (2021) proposed the use of steel balls as ragging material during celestine concentration by jigs. They found that the diameter of the ragging balls and the number of layers played an important role in the separation process. The best results were achieved with balls of $3.1\,mm$ diameter, one layer of ragging balls, and a 15-min separation time, resulting in a celestine concentrate with a grade of $>95\%$ $SrSO_4$ and a recovery of 74.5%. However, it should be noted that they did not test smaller ball diameters, so these conditions may not represent the global optimum.

Falcon concentrators are another gravity separator that has been studied for the processing of celestine. El-Midany and Ibrahim (2011) used a Falcon concentrator to process different synthetic fine celestine ores ($<80\,\mu m$), combining pure samples of celestine and calcite to create mixtures with varying calcite content. The study employed a statistical design of experiments to evaluate the impact of different variables, including calcite content (2.5% to 50%), the rotational speed of the Falcon (motor frequency between 3 and $87\,Hz$) and the fluidisation water pressure (2 to $12\,psi$). The results indicated that lower centrifugal speeds and moderate water pressures yielded the best separation results, with significant calcite removal achieved under these conditions. Moreover, it was observed that the calcite content in the ore significantly influences the separation efficiency.

Another gravity separation equipment used in celestine concentration is the Multi-Gravity Separator (MGS), also known as the Mozley drum. A study by Aslan (2007) used a three-level Box–Behnken factorial design combined with response surface methodology (RSM) to evaluate the effects of drum speed, tilt angle, and shake amplitude on the separation process. The feed corresponded to a sample from the Ulas region of Turkey, with a head grade of 65% celestine associated with gangue minerals such as gypsum and clay. The sample was crushed and ground until 85% of the sample was below $200\,\mu m$. The study found that the optimal conditions for achieving the maximum celestine grade (97%) were a drum speed of $150\,RPM$, a tilt angle of 6°, and a shake amplitude of $20\,mm$. For maximum recovery (98.4%), the optimal conditions were a drum speed of $250\,RPM$, a tilt angle of 2°, and a shake amplitude of $10\,mm$.

Recent advances have incorporated the use of Dense Media Separation (DMS) process to concentrate celestine, as evidenced by the work of Ariza-Rodríguez et al. (2023). Their pilot-scale experiments employing a hydrocyclone focused on the concentration of medium-grade celestine ore. Various heavy minerals were tested to create a dense media with a constant density, which was then fed into the hydrocyclone system to separate celestine minerals into two streams

based on density. The recovered celestine concentrate was evaluated using X-ray Diffraction analysis (XRD), obtaining the best results using a fine ferrosilicon C40 medium ($<40\,\mu m$). The ferrosilicon particles were then recycled using magnetic separation, suggesting the potential for a scalable and sustainable operation. Their study was continued at an industrial scale, using a $250\,mm$ hydrocyclone to concentrate medium-grade celestine ore (75%–85% celestine) using dense ferrosilicon (FeSi) medium (Ariza-Rodríguez et al., 2024). Results showed that the [Sr]/[Celestine ore] was maximised when operating with dense medium densities of 2.75 kg/L, at an inlet pressure of 1.05 bar and inclinations of 18°–20°, achieving a 94% recovery of celestine (68% Sr).

2.3. Froth flotation

Flotation has emerged as a prominent method for concentrating high-grade celestine ores, with extensive research focusing on optimising methodologies to enhance efficiency and selectivity. The exploration of flotation techniques for celestine concentration has been multifaceted, encompassing the selection of collectors, depressants, modifiers, and practical flotation approaches. A summary of the reagents studied in the literature can be found in Table 2.

Bulatovic (2015) offers a comprehensive overview of collector and depressant options tailored for celestine flotation systems. Early studies focused on the use of alkaline salts of oleic acids, such as sodium oleate, as celestine collectors (Glembottskii et al., 1961; Bulatovic, 2015). Notably, several authors (Bulut et al., 2008; Cao et al., 2019; Tian et al., 2021) have provided further evidence that sodium oleate is an effective celestine collector, achieving peak recoveries at pH values between 8 and 9. However, the main practical challenge is that sodium oleate also adsorbs on calcite particles, one of the most common gangues associated with celestine, thus rendering its use ineffective due to lack of selectivity.

For instance, Hernáinz Bermúdez de Castro and Gálvez Borrego (1996) focused on the effect of sodium oleate dosage, temperature and pH in a celestine-calcite system. Their study highlighted the dependency of celestine recovery on sodium oleate concentration, showing an increase in recovery with higher concentrations, particularly at elevated temperatures. Yet, they also observed that quebracho, a vegetable tannin commonly used as a calcite depressant, significantly depressed celestine flotation. Similarly, Cao et al. (2019) used sodium oleate as a celestine collector for celestine-limonite systems, revealing that limonite gangue particles release ferric ions, which strongly depress celestine flotation by reducing adsorption sites for the sodium oleate collector.

These findings, indicating that celestine's interaction with sodium oleate can be depressed with other reagents, have been exploited for systems where celestine is a gangue. For example, recent studies by Tian et al. (2019b, 2021) explored the depression of celestine in systems where sodium oleate served as a fluorite collector. A mixture of $Al_2(SO_4)_3$ and acidified water glass (AWG) was proposed as an effective celestine depressant in a fluorite-calcite-celestine system (Tian et al., 2019b), while sodium polynaphthalene formaldehyde sulfonate (SPS) was shown to depress celestine in a fluorite-celestine system, resulting in a flotation recovery difference between fluorite and celestine of over 75%, with a grade of fluorite concentrates increased by 32.11% at pH 6.0 (Tian et al., 2021).

Another widely studied family of anionic collectors for celestine flotation includes *n*-alkylammonium chloride, sodium *n*-alkyl sulfonate, and sodium dodecyl sulphate (SDS), showcasing high recoveries in the pH range 7 to 9 (Bulatovic, 2015). For instance, López-Valdivieso et al. (2000) showed SDS' effectiveness in recovering celestine over a broad pH range in solutions free of carbonate species, with optimal recovery near pH 7.8. However, they noted diminished performance at pH values above 10 due to the generation of carbonate species with inhibitory effects on collector adsorption. In another study, Martínez-L

Table 2
Summary of main reagents used in celestine flotation.

Reagent	Type	Operational Characteristics	Source
Sodium oleate	Collector	Enhances celestine recovery. Selectivity towards calcite is an issue. Optimal pH range for maximum efficiency: 8–9.	Bulatovic (2015), Hernáinz Bermúdez de Castro and Gálvez Borrego (1996), Bulut et al. (2008), Cao et al. (2019) and Tian et al. (2021)
Sodium dodecyl sulphate (SDS)	Collector	Recovers celestine effectively over a broad pH range. Optimal recovery near pH 7.8. Performance impacted by carbonate species.	López-Valdivieso et al. (2000), Martínez-L et al. (2003), Zeng et al. (2017) and Tian et al. (2019a)
Alkyl sulfosuccinamate (SAM) and Alkyl succinamate (R845)	Collector	Shows promising results in enhancing celestine recovery.	Bulatovic (2015)
Aero825	Collector	Effective in the presence of gypsum at acidic pH (5), yielding high concentrate grades (approx. 94%).	Bulut et al. (2008)
Quebracho	Depressant	Strongly depresses celestine flotation. Originally intended as a calcite depressant.	Hernáinz Bermúdez de Castro and Gálvez Borrego (1996)
Sodium silicate	Depressant	Depressant for calcite, facilitating selective celestine flotation.	Bulut et al. (2008) and Martínez-L et al. (2003)
Citric acid (CA)	Depressant	Selectively inhibits fluorite flotation, enabling successful celestine separation at pH 9–10.	Zeng et al. (2017)
Ethylenediaminetetraacetic acid (EDTA)	Depressant	Inhibits dissolution of calcium ions on fluorite surface, reducing negative influence on celestine flotation.	Tian et al. (2019a)

et al. (2003) showed that SDS was a strong collector for a celestine-calcite system, achieving maximum recoveries of 98% of celestine with a concentrate grade of 96% when combined with hydrated sodium metasilicate as calcite depressant.

Furthermore, studies have explored the use of SDS as a collector combined with different depressants to achieve selective separation in complex mineral systems. For example, Zeng et al. (2017) investigated the flotation separation of celestine from fluorite and calcite using SDS as a collector and citric acid (CA) as a depressant. They found that CA selectively inhibited fluorite flotation at pH 9–10 by forming metal-ligand complexes, enabling successful celestine separation. For a similar celestine-fluorite-calcite system, Tian et al. (2019a) used SDS as a celestine collector and ethylenediaminetetraacetic acid (EDTA) as a fluorite depressant, emphasising its role in inhibiting the dissolution of calcium ions on the fluorite surface and reducing the negative influence on celestine flotation.

Various other celestine collectors have been assessed for celestine-calcite-silica systems, including alkyl sulfosuccinamate (SAM), alkyl succinamate (R845), and sodium oleil tartarate (Igepal T33) (Bulatovic, 2015). These experiments employed oxalic acid and sodium silicate as depressants for calcite and silica. SAM and R845 exhibited notable performance, yielding favourable grades and recoveries of celestine, over 93%, while collector T33 was comparatively less efficient.

Although the aforementioned collectors and depressants represent the most widely studied celestine flotation reagents in the literature, reagent combinations critically depend on the specific ore system. For example, Bulut et al. (2008) focused on the flotation of celestine in the presence of gypsum. They found that potassium oleate was not an effective collector for this system, while sodium silicate was not an effective gypsum depressant. Instead, they showed that the use of $2\,kg/t$ of the anionic collector Aero825 (petroleum sulphonate) in an acidic pH of 5 generated the best results, reaching concentrate grades of ∼94%.

2.4. Other techniques

Less conventional concentration techniques have been proposed in the literature. For example, Ozkan et al. (2006) proposed the use of shear flocculation of celestine using different collectors. Shear flocculation is a process that involves the aggregation of particles in a suspension because of the application of mechanical energy to overcome the energy barrier caused by the electrical charge on the particle surfaces. When hydrophobic particles collide and adhere, the surface energy of the system is reduced by the contact between hydrocarbon

chains, facilitated by the adsorption of a surfactant. The process requires an optimum stirring strength to provide enough kinetic energy for the particles to overcome the energy barrier and form flocs. In their work, Ozkan et al. (2006) found that the shear flocculation of celestine ($SrSO_4$) with sodium dodecyl sulphate (SDS) and Aero 845 surfactants was effective over a broad pH range. The best performance was observed at pH 7, a stirring speed of 500 rpm and a flocculation time of 3 min, although no multivariable optimisation was performed. However, it is important to highlight that the experiments in Ozkan et al. (2006) were performed with pure celestine, ground below $38\,\mu m$, as the objective was to test the formation of flocs. Thus, the experiment did not involve the actual separation of species. Moreover, this particle size is extremely fine for current celestine operations, and would most likely be non-economical for the current strontium market.

Another concentration technique that has been proposed and explored for celestine is oil agglomeration. In this technique, oil is used as an immiscible second liquid phase to bridge fine particles together in a water-based suspension (Capes and Darcovich, 1984; Cebeci and Sönmez, 2004; Duzyol and Ozkan, 2014). The oil droplets preferentially wet the hydrophobic particles, causing the oil-wetted particles to adhere upon collision, forming agglomerates. For the agglomeration of hydrophilic minerals, such as celestine, a two-stage process is typically involved. First, shear flocculation occurs with the aid of surfactants, where mechanical energy is applied to aggregate the particles. Following this, the flocs formed are further agglomerated by the addition of oil (Ozkan et al., 2009). This combined approach makes use of the principles of both shear flocculation and oil agglomeration to enhance the concentration of hydrophilic minerals. It is worth noting, however, that Duzyol and Ozkan (2014) also used pure celestine samples ground below $38\,\mu m$, which does not prove separability nor operates in a feasible particle size range. The work by Cebeci and Sönmez (2004), on the other hand, used real celestine ore samples, ground and sieved to $<212\,\mu m$ ($P_{80} = 150\,\mu m$) for oil agglomeration tests, which is comparable to the particle size used for celestine flotation at industrial scale. Their work achieved celestine recoveries of 89.5% using pH 7, stirring speed $1500\,RPM$, $100\,L/t$ kerosene, $10\,kg/t$ Na oleate, solid ratio 5 wt% and $1\,kg/t$ EDTA; albeit the feed sample had a high grade of almost 95% $SrSO_4$.

Leaching offers an alternative approach for processing strontium minerals. While most industrial operations use leaching as a metallurgical step, treating pre-concentrated celestine to produce $SrCO_3$ (see Section 3), research efforts have explored the direct leaching of celestine ore. For instance, Kocan and Hicsonmez (2019) studied

the dissolution of untreated celestine, composed of 62.55% celestine, 33.55% bassanite, 2.2% quartz and 1.7% of other minerals. They found that the dissolution rate increased with higher reaction temperature, stirring speed, NaOH concentration, and reaction time, but decreased with larger particle size and higher solid–liquid ratio. Under optimal conditions, strontium extraction exceeded 95%, reaching completion in 210 min.

2.5. Industrial concentration case studies

To further illustrate the processing of celestine at an industrial scale, four case studies are analysed here. The first two case studies correspond to Spanish mines, namely the current processing operations at Canteras Industriales and the operation of Minas de Ezcúzar. The third case corresponds to an operation in China. Although China and Iran are global leaders in celestine production, comprehensive data for discussion are limited, highlighting the scarcity of information available for the beneficiation of this critical mineral. In fact, no information is publicly available regarding celestine production in Iran. The fourth case study presented corresponds to a proposed gravity separation processing plant for the Wadi-Essel deposit in Egypt.

2.5.1. Case study 1: Canteras industrials – Minas de Montevive, Granada, Spain

Canteras Industriales S.L. operates the largest reserve of celestine in the EU, located in Montevive, Spain. The deposit is commonly associated with coastal marine carbonate and evaporite deposits (Ariza-Rodríguez et al., 2022). Representative samples contain approximately 73.3% celestine, while the main gangue minerals are calcite (15.4%), quartz (4.6%), magnesite (1.7%) and haematite (1.7%), as described in Ariza-Rodríguez et al. (2022).

Ore processing operations at Canteras Industriales are based on traditional mining activities for coarse particle processing using crushing, screening, sorting, and grading, followed by conveying and loading. The available mineral resources consist of material from both the active quarry front and medium- to low-grade dumps generated in the past, with a celestine content ranging from 60% to 80%. Ore with grades below 70% celestine cannot be commercialised, and thus, it has been stored in dumps, recognised as environmental liability. The concept of "environmental liability" in this context refers to the portion of the material that remains unmarketable after processing and must be managed responsibly through reclamation activities.

The current operation aims to concentrate this material using dense media separation, spirals, and other beneficiation methods to increase the grade to a marketable minimum of 80%–85%. Once the highest possible recovery is achieved, the remaining low-grade waste will be repurposed for quarry backfilling, reducing the environmental impact. Current production is estimated at 350 t/day, with a water consumption of 12 m³/day for irrigation of the track and 4 m³/day for wetting the material in dry periods.

Fig. 7 illustrates the ore processing operations conducted with mobile machinery at Canteras Industriales. Initially, an excavator extracts celestine ore, loading it onto a dumper truck for transport to the processing site. The RoM ore undergoes comminution processes, starting with screening using a mobile grizzly bar screen, resulting in two fractions, one coarse and one finer than 100 mm. The >100 mm fraction is further reduced in size in a mobile impact crusher to achieve a <100 mm size. The material is considered soft and has limited wear on the processing equipment.

The combined <100 mm fraction undergoes additional size classification in the same mobile screen, resulting in coarse (+20 mm −100 mm), medium (+6 mm −20 mm), and fine (<6 mm) size fractions. The coarse fraction is further reduced using a crushing bucket on the excavator arm, producing product P2 with a size fraction of <35 mm. The remaining medium and fine size fractions are classified as product P1 (+6 mm −20 mm) and tailings, respectively, with wheel loaders facilitating material transportation between the mobile crusher and screen, indicating
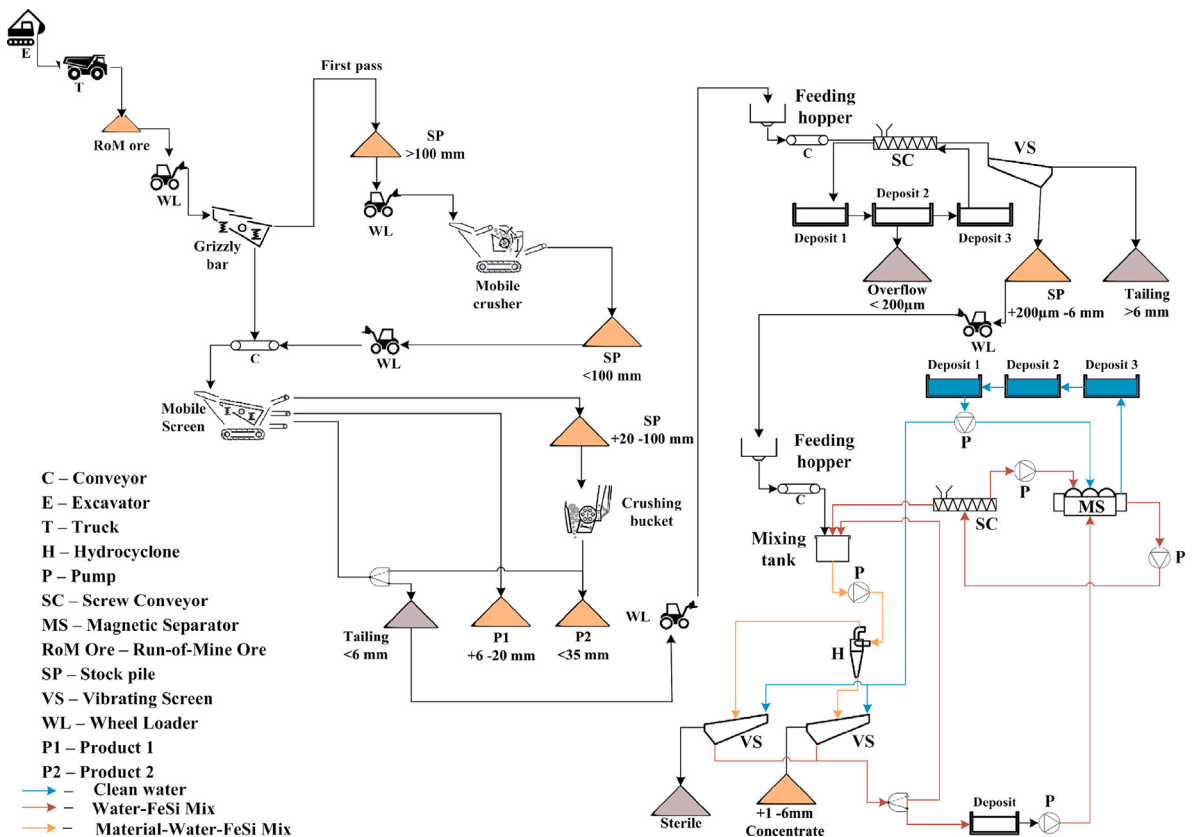

C – Conveyor
E – Excavator
T – Truck
H – Hydrocyclone
P – Pump
SC – Screw Conveyor
MS – Magnetic Separator
RoM Ore – Run-of-Mine Ore
SP – Stock pile
VS – Vibrating Screen
WL – Wheel Loader
P1 – Product 1
P2 – Product 2
→ – Clean water
→ – Water-FeSi Mix
→ – Material-Water-FeSi Mix

Fig. 7. An overview of the celestine processing flowsheet at Canteras Industriales.
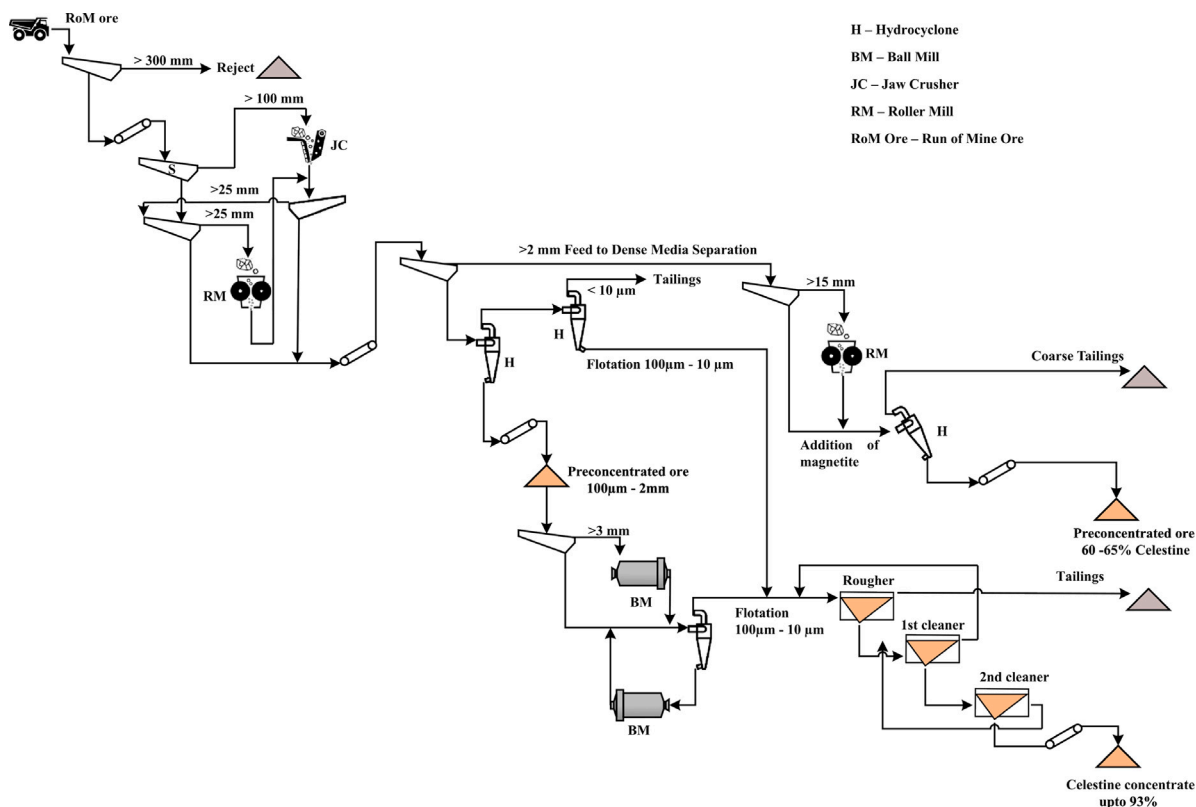
Fig. 8. An overview of the celestine concentration process at Minas de Ezcúzar.

the absence of fixed conveyors at the processing site. It is important to recognise that the site may adopt various process configurations tailored to handle diverse ore grades and achieve specific size fractions.

The tailings from the comminution process are later treated in a desliming and dense separation process to enrich the tailings and produce celestine concentrate. At first, the tailings are deslimed in a desliming unit to remove material fractions <200 μm, while a vibrating screen is used to remove the oversize and material fractions >6 mm. The material (+200 μm −6 mm) from the screen is sent to dense media separation, where it is mixed with ferrosilicon and water, and fed to an inclined hydrocyclone. This process, based on the laboratory-scale work of Ariza-Rodríguez et al. (2023), produces a valuable celestine concentrate from fresh tailings.

2.5.2. Case study 2: Minas de Escúzar – Granada, Spain

The beneficiation of celestine at Minas de Escúzar, thoroughly detailed by Carvajal-Lachica (2019), is summarised here and schematised in Fig. 8. The processing plant includes both density separation and flotation, to separate celestine from the main gangue minerals, namely calcite ($CaCO_3$), gypsum ($CaSO_4 \cdot 2\,H_2O$) and dolomite ($CaMg(CO_3)_2$). The run-of-mine ore is screened, with the coarse fraction (>100 mm) being crushed using a jaw crusher. The product is screened again in a closed circuit with a roller mill, producing material at 100% <25 mm. The ore is then classified into two fractions, coarse and fine, with a 2 mm screen cut. The coarse fraction (+2 mm −25 mm) is sent to dense media separation for pre-concentration. The fine fraction (<2 mm) is sent to a hydrocyclone. The overflow of the hydrocyclone (<100 μm) is sent to flotation for further concentration, while the underflow (+100 μm −2 mm) is considered a pre-concentrated mineral and sent to a stockpile.

The density separation for the coarse fraction is achieved using dense media hydrocyclones. The feed (+2 mm −25 mm) is first screened at 15 mm, with the coarse fraction being crushed using a roll mill in an open circuit. The material under 15 mm is then pumped into a dense

media separation process in an inclined hydrocyclone. Leveraging the specific gravities of celestine (~4), calcite (2.7), and gypsum (2.3), a dense media slurry is prepared using finely ground magnetite and water, achieving a specific gravity of 3.5 in the slurry. The overflow contains the gangue material and is sent to the tailings, while the celestine-rich underflow (60%–65% celestine) is sent to the pre-concentrate stockpile. The ore from the preconcentrated stockpile is sent to further comminution through a closed circuit with ball mills and hydrocyclones until a particle size of under 100 μm is achieved to be sent to froth flotation.

Celestine flotation aims to separate celestine from calcite and gypsum. To this end, different reagents are added. Sodium carbonate (Na_2CO_3) is added as a gypsum depressant by modifying the pH. Sodium and magnesium sulphate are added as modifiers. A final concentrate of celestine is produced, with a grade of greater than 90%.

2.5.3. Case study 3: Xinjiang mine – Xinjiang, China

The information regarding Chinese operations is scarce. In fact, the details reported in this case study, as well as the flowsheet depicted in Fig. 9, are based on information published by the equipment manufacturing company (Forui Mining, 2021).

The RoM celestine ore is hauled to the plant for processing, where two jaw crushers are used in series as primary and secondary crushing stages to reduce particle size. The ore is screened using circular vibrating screens to separate it based on size criteria. The coarse fraction >30 mm is returned to the secondary crusher in a closed circuit, the middlings (+8 mm −30 mm) are directed towards a series of sorting jigs, while the finer fraction <8 mm are handled separately. The +8 mm −30 mm fraction is sent to an AM30 jigger for sorting, while the <8 mm fine fraction is sent to an LTA1010/2 jigger. The AM30 jigger produces a coarse concentrate of celestine and tailings. The tailings of the AM30 jigger are finely crushed by a compound crusher and sent to the LTA1010/2 jigger together with the fine fraction. Finally, fine-grained celestine concentrate and final tailings are obtained.
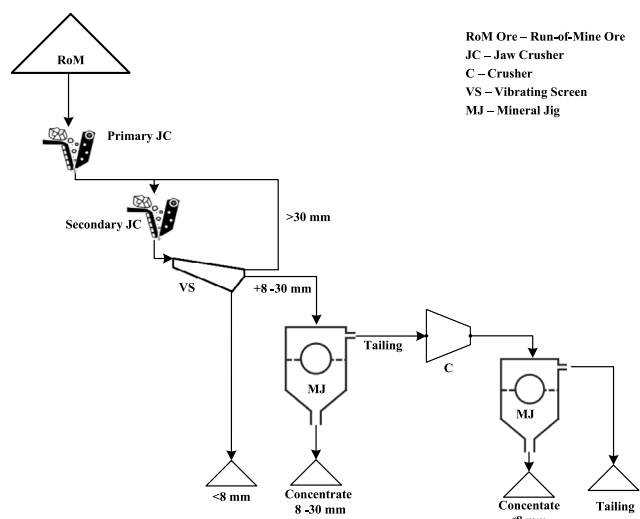
Fig. 9. An overview of the celestine concentration process in a Chinese mine in Xinjiang.
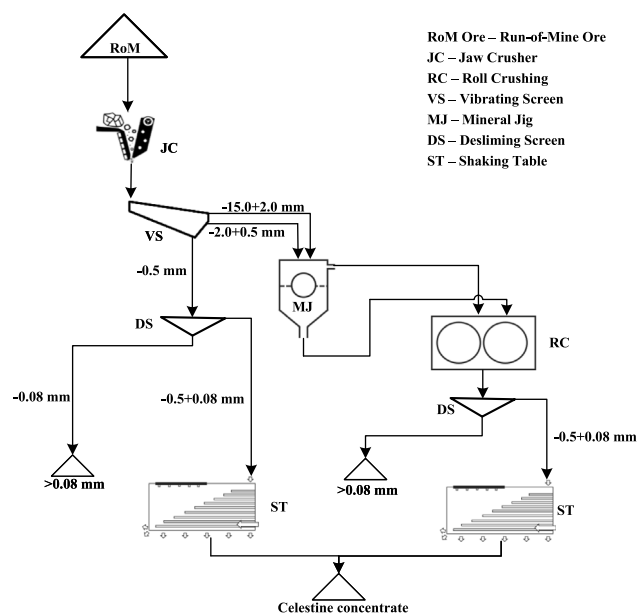*Source:* Based on Forui Mining (2021).

Fig. 10. Jig and shaking table flowsheet proposed for the Wadi-Essel celestine ore.
Source: Based on Selim et al. (2010).

2.5.4. Case study 4: Wadi-Essel - Egypt

A substantial Zn-Pb-celestine deposit is located in the Eastern Desert of Egypt. This Mississippi Valley Type (MVT) deposit has been recently characterised (Saad, 2023). Previous investigations have estimated celestine reserves in the Wadi-Essel region to be approximately 2.3 million tonnes (Hessien et al., 2009; El-Amir et al., 2021). Comprehensive characterisation of large ore samples from the Wadi-Essel deposit by Selim et al. (2010) and Sobhy et al. (2021) has revealed a celestine head grade of approximately 67%, with a relatively high limestone content of up to 28% $CaCO_3$.

Despite the absence of mining operations at this deposit, the study by Selim et al. (2010) proposed a processing flowsheet based on laboratory-scale experiments. The proposed flowsheet is illustrated in Fig. 10.

In their work, Selim et al. (2010) proposed the use of a jaw crusher, followed by a series of screening stages. The coarse fraction ($+0.5$ mm

-15 mm) is sent to a jig to generate a coarse concentrate. The jig tails are then sent to a roll mill to reduce to <0.5 mm. Both fine fractions (<0.5 mm), the one generated after primary crushing and crushed tailings, are deslimed using a screen. The finer slimes ($<80\,\mu$m) are discarded as final tailings, and the coarse fraction ($+80\,\mu$m $-500\,\mu$m) is sent to a shaking table to produce a fine celestine concentrate.

3. Strontium metallurgy

Once a high-grade celestine concentrate has been attained, the next step is its conversion into strontium carbonate ($SrCO_3$). Several techniques have been explored for converting $SrSO_4$ into $SrCO_3$, with the two most common being the *black ash* method (roasting and leaching) and the *direct conversion* (two-leaching stages).
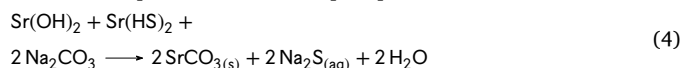
In the black ash method, celestine transforms into strontium sulphide (SrS) typically at temperatures ranging from 1100 °C to 1200 °C, facilitated by the presence of metallurgical grade coke or petroleum coke (Erdemoğlu and Canbazoğlu, 1998; Sonawane et al., 2000; Erdemoğlu, 2009). Within the kiln, chemical reactions occur, leading to the carbothermic reduction of celestine, as described in Eqs. (1) and (2) (Sonawane et al., 2000).

$$SrSO_4 + 2\,C \longrightarrow SrS + 2\,CO_2 \tag{1}$$

$$SrSO_4 + 4\,CO \longrightarrow SrS + 4\,CO_2 \tag{2}$$

The resultant product of this reductive roasting process is a dark ash, primarily composed of SrS, which readily breaks down when exposed to hot water, as described in Eq. (3) (Erdemoğlu and Canbazoğlu, 1998; Owusu and Litz, 2000).

$$2\,SrS + 2\,H_2O \longrightarrow Sr(OH)_2 + Sr(HS)_2 \tag{3}$$
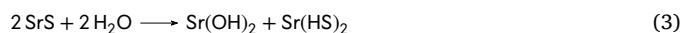
Following the leaching of the dark ash with hot water and the subsequent removal of insoluble metal sulphides and other impurities, the resulting solution is treated with either carbon dioxide or sodium carbonate (Eq. (4)) to induce the precipitation of strontium carbonate.

$$\begin{aligned} Sr(OH)_2 + Sr(HS)_2 + \\ 2\,Na_2CO_3 \longrightarrow 2\,SrCO_{3(s)} + 2\,Na_2S_{(aq)} + 2\,H_2O \end{aligned} \tag{4}$$
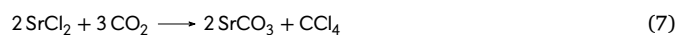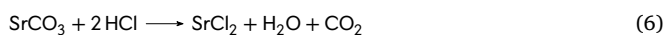
The precipitate is dried and screened, with the reaction conditions and drying techniques determining the particle size of the product (Erdemoğlu and Canbazoğlu, 1998).
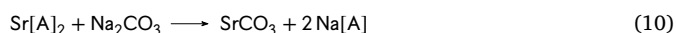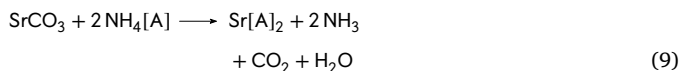
The direct conversion method, also known as the double decomposition process, consists of reacting finely powdered celestine concentrate with sodium carbonate (Na_2CO_3) (Iwai and Toguri, 1989; Carrillo et al., 1995; Castillejos et al., 1996), ammonium carbonate ($(NH_4)_2CO_3$) (Buda, 1987) or ammonium bicarbonate (NH_4HCO_3) (Erdemoğlu and Canbazoğlu, 1998; Chen and Zhu, 2000; Zoraga and Kahruman, 2014) and treating it with steam (95 °C) for 1 to 3 h (Erdemoğlu and Canbazoğlu, 1998; Aydoğan et al., 2006). This process generates crude strontium carbonate and sodium sulphate, as shown in Eq. (5).

$$SrSO_4 + CO_3^{2-} \longrightarrow SrCO_3 + SO_4^{2-} \tag{5}$$
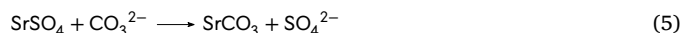
Since crude $SrCO_3$ is impure and contains undissolved solids, it is decomposed using HCl solutions to obtain aqueous $SrCl_2$ (Eq. (6)). This salt is reacted with CO_2 (Eq. (7)) or Na_2CO_3 (Eq. (8)) to produce pure $SrCO_3$, thus the name of double decomposition (Xu and Zhu, 2005; Aydoğan et al., 2006; Castillejos et al., 1996).

$$SrCO_3 + 2\,HCl \longrightarrow SrCl_2 + H_2O + CO_2 \tag{6}$$

$$2\,SrCl_2 + 3\,CO_2 \longrightarrow 2\,SrCO_3 + CCl_4 \tag{7}$$

$$SrCl_2 + Na_2CO_3 \longrightarrow SrCO_3 + 2\,NaCl \tag{8}$$

Due to the high consumption of HCl, this second stage has become uneconomic for some operations. An alternative for the second stage of the direct conversion method consists of using a high concentration of an ammonium salt with anions that can form soluble strontium salts, such as NH_4NO_3, NH_4Cl, $(NH_4)_2S$, NH_4HCOO^- or $NH_4CH_3COO^-$ (Xu and Zhu, 2005; Zoraga and Kahruman, 2014; Zoraga et al., 2016), obtaining the process described in Eqs. (9) and (10).

$$SrCO_3 + 2\,NH_4[A] \longrightarrow Sr[A]_2 + 2\,NH_3$$
$$+ CO_2 + H_2O \qquad (9)$$

$$Sr[A]_2 + Na_2CO_3 \longrightarrow SrCO_3 + 2\,Na[A] \qquad (10)$$

Besides the black ash and the direct conversion methods, other techniques have been explored in the literature. Among them, the most widely studied alternative process is the dry mechanochemical treatment of celestine. Zhang and Saito (1997) proposed for the first time the room temperature processing of celestine by milling a mixture of $SrSO_4$ concentrate with a dry sodium hydroxide powder in a planetary mill. As shown in Eq. (11), the celestine particles spontaneously react with NaOH, forming strontium hydroxide.

$$SrSO_4 + 2\,NaOH \longrightarrow Sr(OH)_2 + Na_2SO_4 \qquad (11)$$

$$Sr(OH)_2 + CO_2 \longrightarrow SrCO_3 + H_2O \qquad (12)$$
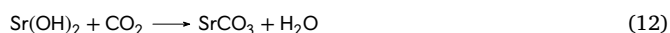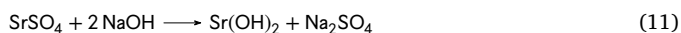
The strontium hydroxide is subsequently converted into strontianite by exposure to the CO_2 in the air (Eq. (12). This double-step reaction has led some researchers to refer to this method as an indirect mechanochemical process. The role of milling is to provide energy and mixing to accelerate the reaction rate and to increase the fresh surface area for reaction.

Other authors have studied the thermodynamics and kinetics of direct mechanochemical conversion of celestine using sodium carbonate as a carbonation agent, following Eq. (13).

$$SrSO_4 + Na_2CO_3 \longrightarrow SrCO_3 + Na_2SO_4 \qquad (13)$$
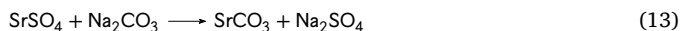
For instance, Obut et al. (2006) showed that the direct mechanochemical treatment of celestine with sodium carbonate could work in both dry and wet milling, obtaining the best conversion results (93%) with dry processing with 40 min activation time. Similar results have been obtained by Erdemoğlu et al. (2007) – achieving full conversion celestine into $SrCO_3$ within 45 min of processing at 0.1 solid to liquid ratio when 50% excess sodium carbonate was used –, and by Setoudeh et al. (2010) – showing that >90% conversion can be achieved after 30 min and <99% conversion of celestine to $SrCO_3$ is obtained in 30 min by increasing the molar ratio of Na_2CO_3:$SrSO_4$ to 1.3:1.

Other reagents for the direct dry mechanochemical process have been studied instead of sodium carbonate. For example, Setoudeh and Welham (2011, 2012) proposed using aluminium (Eq. (14)) and magnesium (Eq. (15)), respectively, in a planetary mill to react with celestine and produce SrS, replacing the black ash method.

$$3\,SrSO_4 + 8\,Al \longrightarrow 3\,SrS + 4\,Al_2O_3 \qquad (14)$$

$$SrSO_4 + 4\,Mg \longrightarrow 4\,MgO + Srs \qquad (15)$$

However, XRD analysis showed that the aluminium method was not successful, as some $Sr\text{–}Al\text{–}O$ compounds such as $Sr_3Al_{32}O_{51}$ ($3\,SrO \cdot 16\,Al_2O_3$) and $SrAl_2O_4$ ($SrO \cdot Al_2O_3$) were formed instead of pure Al_2O_3. The results with magnesium were more promising, showing that the celestine and Mg mixture initiated a self-sustaining reaction after 10 min of milling. The highly crystalline SrS and MgO products indicated an exothermic process with localised temperatures over 1500 °C, with the reaction reaching about 84% completion after 20 min of milling.

Another reagent proposed in the literature is $(NH_4)_2CO_3$ (Bingöl et al., 2012b,a), as shown in Eq. (16).

$$SrSO_4 + (NH_4)_2CO_3 \longrightarrow SrCO_3 + (NH_4)_2SO_4 \qquad (16)$$
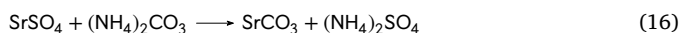
After optimisation, a $SrCO_3$ conversion of >99% was obtained, using 9.24 of ball to grinding material mass ratio, 1.86 of $(NH_4)_2CO_3$ to $SrSO_4$ mole ratio and 400 rpm of the rotational speed of the mill. The $(NH_4)_2SO_4$ obtained as a byproduct was crystallised. The main advantage of this proposed system is that the ammonium sulphate produced can be used as an artificial nitrogenous fertiliser (Bingöl et al., 2012b).

4. Future of strontium

4.1. Circularity and environmental assessment

The recognition of strontium as a CRM in the European Union is expected to bring more attention to the market, spurring an increase in production and demand. Nevertheless, despite the clear supply issues for strontium, it has been widely discussed that creating a universal list of critical metals is impractical (Panousi et al., 2016). While many countries have developed their own lists, with metals being added or removed upon each revision, these lists often necessitate setting arbitrary thresholds in criticality. The variability in supply and demand among different users is so extensive that it is more appropriate to view criticality as a spectrum rather than a binary state (Panousi et al., 2016). Yet, as strontium criticality is strongly associated with its Supply Risk, SR = 6.5 (European Commission, 2023), it is important to shift the market and research focus towards securing future supply and enhancing its circularity. Furthermore, some studies have recommended the implementation of European stockpiling of CRMs, which could help mitigate supply risk and ensure a steady supply of strontium (Ragonnaud, 2023; Orberger et al., 2024).

Industrial minerals in general, and celestine in particular, have experienced an increase in value in the last years. The average price of celestine rose from 78 USD/tonne in 2018 to 114 USD/tonne in 2022, resulting in an increase of approximately 46% in just four years (USGS, 2022). The exploitation of celestine in Granada and especially in the Montevive mine is remarkable, as it is the only producer at the European level and one of the few worldwide. Consumption of total strontium and strontium compounds increased significantly in 2022. Furthermore, celestine consumption increased by 10% compared to 2019, probably due to improved economic conditions after the recession caused by COVID-19 (USGS, 2023).

Circular economies rely on the incorporation of recycled materials to replace primary raw materials, yet the share of recycled strontium in the European Union remains negligible, as reported by the European Commission (2023). The "End-of-Life Recycling Input Rate" (EOLRIR), a key parameter that represents the supply of secondary raw materials, reports a 0% rate for strontium in the European Union (European Commission, 2023).

However, there is an untapped potential in the recycling of strontium from waste CRTs. Since the late 1990s, efforts focused on the development of recycling technologies for producing secondary raw materials from CRT glass (Andreola et al., 2007; Herat, 2008), associated with the Waste Electrical and Electronic Equipment (WEEE) directive. The main challenges for CRT glass recycling are the high contents of lead and cadmium in the glass, as well as the reluctance from glass fibre manufacturers to accept high contents of strontium in their process (Herat, 2008). Consequently, most efforts focused on the extraction and "detoxification" of the glass, involving techniques such as strontium leaching from foam glass (Yot and Méar, 2011). Similarly, Xing et al. (2018) proposed a process for the extraction of barium and strontium from waste CRT glass based on pyrometallurgy and phase separation, achieving the removal of 99.4% of the strontium.

In recent years, research efforts have focused on the recycling of CRT glass through the production of ceramics. For example, Karaahmet and Cicek (2019) proposed a methodology for recycling CRT glass with high barium and strontium content to produce transparent ceramic frits, as the presence of strontium resulted in glossy surfaces

with a more decorative appearance, often called a "soft glaze". Other strontium-recycling efforts have focused on the recycling of strontium ferrite waste from permanent magnet production (Bollero et al., 2017) and the recycling of high-purity strontianite from sludge using acid leaching (Bian et al., 2020). Yet, industrial recycling efforts are still lacking and are far from replacing the demand for primary extraction.

While emphasising circularity is relevant for the future, it is equally crucial to assess the environmental impact of strontium production from both primary and secondary sources. Although the European Union is one of the major producers of strontium globally, with a share of 34%, there is a notable absence of studies investigating the environmental impacts of its production process. Addressing this gap, the European project ROTATE (ROTATE, 2022), focused on providing environmental solutions for the mining and quarrying industry, has selected the Spanish celestine mine of Canteras Industriales (see Fig. 7) as a case study. For this specific site, the project aims to assess and quantify the environmental impacts of the produced celestine concentrate in different size fractions and develop a recovery process to treat celestine tailings to recover valuable mineral particles.

Apart from the circularity of the material, it is important to consider the environmental impact of the value chain, using the life-cycle perspective on the production of concentrates. A detailed review can be found in Marmiroli et al. (2022). The environmental impact assessment (e.g., Life Cycle Assessment (LCA)) typically includes multiple aspects such as the extraction, transport, and processing of virgin ore to produce celestine concentrate. The impact originates due to resource consumption (*e.g.*, diesel, electricity, water, etc.), as well as waste generation (hazardous and non-hazardous waste) (Lee et al., 2024). Additionally, the transportation distance and mode of transport from the different value-adding activities for producing strontium-based products revolve around the transportation of celestine concentrate, connecting multiple production facilities that exist in various regions of the world. This transportation of concentrate can have a global environmental impact even greater than that of the production process itself. Therefore, relocating more value-adding processes closer to the extraction (mining) site can potentially increase economic revenue and reduce environmental impact by lowering emissions from transportation. This perspective is only viable if the metallurgical processing know-how is developed within the European Union. Future work can include quantification of environmental impacts of strontium production using LCA due to the complexity of existing supply chain network.

4.2. Novel and future applications for strontium

In recent decades, the application landscape for strontium has evolved significantly due to technological changes. Following the decline in CRT glass production, a major use of strontium has been in the production of ceramic magnets, as shown in Figs. 4 and 5.

Almost 80% of the permanent magnets contain rare-earth elements (REE), which are expensive and primarily dominated by Chinese production (Grand View Research, 2023; Guzmán-Mínguez et al., 2020). Thus, the emergence of strontium-based magnets as an alternative to REE has caught the attention of researchers and may play a fundamental role in the future of strontium. Examples include the development of FeCo nanowire-strontium ferrite powder composites (Guzmán-Mínguez et al., 2020), the first dense strontium hexaferrite-based REE-free composite permanent magnets assisted by cold sintering process (García-Martín et al., 2022), and anisotropic strontium hexaferrite nanomagnets (Lee et al., 2020). Anisotropic strontium ferrite powder is used in the production process to tailor the magnetic properties of permanent magnets. Przybylski et al. (2019) showed that increasing the amount of strontium ferrite powder leads to improvements in magnetic properties and hardness, although it decreases tensile strength.

Beyond magnets, strontium-based nanoparticles find applications in medicine and environmental sciences, particularly in bone and tissue engineering due to their similarities with essential trace metals like calcium and magnesium (Mukherjee and Mishra, 2021). Additionally, strontium-aluminate-based materials are being explored for smart mechanoluminescent phosphors, offering applications in stress visualisation, crack detection, advanced lighting, imaging, and luminous fabrics (Huang et al., 2023). Smart windows made of recycled polycarbonate plastic immobilised with strontium aluminate phosphor nanoparticles are proposed for maximising light transmission with minimal energy consumption (El-Hefnawy et al., 2023), while other studies have explored strontium-aluminate for afterglow and photochromic translucent wood in smart window applications (Binyaseen et al., 2024).

5. Conclusions

This comprehensive review highlights the multifaceted aspects of strontium, spanning its properties, global reserves, market dynamics, and beneficiation processes, while identifying future challenges around its extraction, beneficiation, and use. Recognised as a Critical Raw Material by several major economies, strontium's strategic significance is underscored by its diverse applications, shifting from its use in Cathode-Ray Tube (CRT) glass, which drove Sr demand until the mid-2000s, to current roles in pyrotechnics, drilling fluids, and ceramic magnets.

The mineralogical profile of strontium is dominated by celestine ($SrSO_4$) and strontianite ($SrCO_3$), with celestine being the principal commercial source. Significant global reserves are found in China, Iran, Spain, and Mexico, though economically viable deposits are relatively scarce. Market dynamics reveal fluctuating production patterns influenced by technological advancements and shifts in end-use applications.

Beneficiation of strontium-bearing minerals, particularly celestine, has progressed from manual sorting to more sophisticated techniques such as size separation, gravity separation, flotation, and dense media separation. Recent studies have implemented dense media separation, utilising fine ferrosilicon media in hydrocyclone systems, resulting in enhanced recovery and purity of celestine concentrates. Additionally, unconventional techniques like shear flocculation show promise, achieving optimal results with sodium dodecyl sulphate (SDS) and Aero 845 surfactants.

The detailed examination of various industrial case studies reveals significant advancements and variations in celestine processing across different geographical regions. Operations at Canteras Industriales in Spain integrate mobile machinery and dense media separation to optimise ore recovery from waste dumps, achieving an 80% recovery rate. The Minas de Escúzar case study illustrates a sophisticated process combining density separation and flotation, achieving high-grade celestine concentrates through precise comminution and reagent addition. Meanwhile, robust beneficiation techniques in China, involving primary and secondary crushing and sorting jigs, highlight their leading role in celestine production, though detailed process data from this and other important regions such as Iran remain scarce.

The future of strontium production, as well as other critical minerals, hinges on improving its circularity and addressing environmental impacts. The negligible EOLRIR for strontium in the European Union highlights the need for intensified recycling efforts, particularly from waste CRTs and strontium ferrite waste. Emerging applications in magnet technology, medicine, and smart materials present new opportunities, potentially reducing reliance on rare-earth elements and fostering innovation.

Addressing the environmental implications of strontium production is imperative. Initiatives like the ROTATE project, funded by the European Union, aim to provide sustainable solutions and environmental assessments for mining activities, exemplified by the case study at Canteras Industriales. Such efforts are crucial for establishing environmentally responsible practices in the strontium supply chain.

The advancement of celestine beneficiation techniques, coupled with a focus on recycling and environmental sustainability, is instrumental in meeting the growing demand for strontium. Continued

research and innovation are essential to overcoming current challenges and harnessing the full potential of this critical mineral. As the demand for strontium evolves, driven by emerging technologies and expanding industrial applications, the sustained study and optimisation of strontium extraction and processing methodologies will play a pivotal role in ensuring a stable supply chain and enhancing the purity of strontium compounds.

CRediT authorship contribution statement

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

Declaration of competing interest

Co-author Pablo R. Brito-Parada is Editor-in-Chief of Minerals Engineering journal and was not involved in the handling of this submission. Co-authors Francisco Ortega and Noemi Ariza-Rodríguez are affiliated with Canteras Industriales S.L., a celestine mine highlighted in this paper.

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Data availability

No data was used for the research described in the article.

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