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Global Inventory and Spatial Analysis of Rare Earth Element Emissions from the Cement Industry

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Abstract. Rare earth elements (REEs) are increasingly recognized as environmentally relevant trace pollutants in industrial particulate emissions, yet their release from the cement sector remains poorly constrained at the global scale. This study develops a global unit-level inventory of cement-related REE emissions by integrating facility-level cement and clinker data, technology information, socioeconomic indicators, and published element-specific emission factors, and further evaluates mitigation potential through scenario analysis. The global cement sector was estimated to emit 248 t of REEs, with a 95% uncertainty interval of 44.3–739.0 t, and emissions were distributed highly unevenly across regions and countries. Asia-Pacific was the dominant contributor, followed by Africa, while China, India, and Egypt were the leading national emitters. Elementally, emissions were strongly skewed toward Ce, La, Nd, and Y, which together accounted for nearly 85% of the total burden. This uneven spatial distribution was mainly associated with dust removal, industrial output and GDP-related variables, as shown by SHAP-based attribution analysis. Country-level ecological screening showed only weak correlations between per-capita REE emissions and disease burden, suggesting that national emission burden alone has limited explanatory power for public-health outcomes. Scenario analysis further showed that dust-removal upgrading produced the largest mitigation effect, reducing global PM-bound REE emissions by 49.8%. Overall, this study provides a global high-resolution framework for quantifying cement-related REE emissions and identifying region-specific priorities for emission control.

Keywords: rare earth elements, cement industry, emission inventory, spatial patterns, SHAP analysis

1. Introduction

Rare earth elements (REEs) are increasingly recognized not only as critical materials for modern industry, but also as environmentally relevant trace constituents in anthropogenic emission systems. Owing to the distinctive electronic structure of the lanthanides, REEs are widely used in catalysts, electronics, alloys, lighting technologies, and low-carbon energy systems [1, 2]. At the same time, their environmental significance extends beyond their technological value. Once released from mineral feedstocks, REEs may occur in particulate-bound forms and enter atmospheric transport and deposition pathways. Toxicological studies have shown that selected REE compounds and REE-

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bearing particles can induce oxidative stress, inflammatory responses, DNA damage, and pulmonary effects [1, 3]. Consequently, the environmental relevance of REEs cannot be understood solely from their resource importance; it also requires source-specific quantification of their industrial release, especially from sectors that process large volumes of mineral materials and generate substantial particulate emissions.

Among such sectors, cement manufacture is likely to represent a major but still insufficiently constrained pathway of atmospheric REE release. Cement manufacture is one of the largest industrial systems for extracting, thermally transforming, and redistributing geological materials. Although cement forms only a fraction of concrete by mass, its annual production on the order of 4 billion tonnes supports a much larger flow of aggregates, reinforced materials and construction stocks [4, 5]. This material demand is closely tied to urbanisation, infrastructure construction and economic development, particularly in rapidly developing regions where demand for housing, transport networks and public facilities continues to drive cement consumption [6-8]. The sector is therefore both a major indicator of infrastructure development and a major industrial source of environmental pressure. Cement production is energy intensive, and its CO_2 emissions arise from both fuel combustion and carbonate decomposition during clinker production [8, 9]. Industry-wide review studies have extensively assessed the cement sector within conventional air-pollution and carbon-inventory frameworks [9-12]. Field and model studies have further quantified cement-related particulate matter, NO_x, SO_x, mercury and other heavy-metal emissions [13-15]. However, from the perspective of trace-element redistribution, cement production also represents a high-throughput mineral-processing system in which raw materials are heated, chemically transformed, and partly emitted through particulate pathways. This makes the sector a plausible industrial source of REE emissions, yet one that remains poorly characterised at global scale.

Recent evidence indicates that cement production may be an important industrial source of atmospheric REEs. Yun et al. [3], based on fine-particulate measurements from 114 large industrial sources across 13 sectors in China, reported that cement-related sources contributed the largest share of PM-bound REE emissions among the sectors investigated. This finding shifts cement manufacture from being viewed solely as a conventional carbon- and particle-emitting industry to being recognised as a potentially important source of industrial REE release. Nevertheless, current evidence remains limited in spatial and technological resolution. Cement production differs strongly among countries, plant systems and pollution-control conditions. Aggregated sector-level estimates can identify cement manufacture as an REE source, but they provide limited capacity to resolve how emissions vary with clinker output, plant configuration, dust-removal performance and regional industrial structure. This limitation is particularly important because recent cement inventories have shown that unit-level activity data and control-technology information can reduce uncertainties that arise from average emission factors and aggregated activity data [14, 15]. For REEs in particular, a higher-resolution unit-level inventory is needed not only to quantify total emissions, but also to resolve their elemental composition, spatial concentration, and potential mitigation levers within heterogeneous global production systems.

Against this background, this study develops a global unit-level inventory of REE emissions from the cement industry. By integrating cement production statistics, technology-structure information, and published emission factors, the study estimates atmospheric REE releases at the production-unit scale and then aggregates these estimates to national, regional, and global levels. This framework allows spatial distribution, development-group differences and elemental composition to be assessed in a consistent accounting system. The analysis further links emission variation to production scale, dust-removal performance, plant configuration, economic structure and emerging low-carbon

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technologies through machine-learning attribution. By moving from broad sectoral recognition to a spatially explicit unit-level inventory, this study provides a quantitative basis for understanding the industrial redistribution of geogenic trace elements through the cement sector, evaluating the environmental relevance of REE emissions, and identifying region-specific priorities for emission control.

2. Methods and materials

2.1. Data sources and preprocessing

Multiple datasets were integrated to construct the global cement-related REE emission inventory. Plant-level cement and clinker data were obtained from the Global Cement and Concrete Tracker (GCCT) developed by Global Energy Monitor. The GCCT provides asset-level information on cement and clinker plants worldwide, including plant location, operating status, cement capacity, clinker capacity, plant type and production type. It also records technology-related indicators, such as alternative fuel use, clay calcination and CCS/CCUS deployment and selected technology indicators [16]. These data were used to construct the unit-level production dataset and to support the estimation and spatial aggregation of cement-related REE emissions.

Socioeconomic and health datasets were used as supplementary data for the driver and correlation analyses. GDP, GDP per capita and industrial output were obtained from World Bank Open Data and used to represent national economic and industrial conditions [17-19]. Country-level disease incidence and mortality data were obtained from the Global Burden of Disease (GBD) Results Tool and used for ecological correlation analysis only [20]. Before analysis, country names, units and temporal coverage were harmonised across datasets. Records with missing variables required for a specific analysis were excluded from that analysis.

2.2. Estimation of cement-related REE emissions

A bottom-up emission-factor approach was used to estimate cement-related REE emissions at the production-unit level [3, 14, 15, 21]. Following Yun et al. [3], emissions of REE element e from cement production unit i were calculated as:

$$E_{i,e} = A_i \times \bar{C}_e \times EF_i = A_i \times \bar{C}_e \times P_{i,j} \times (1 - \eta_{i,k}) \quad (1)$$

where i, e, j and k denote the cement production unit, REE element, production section and end-of-pipe treatment technology, respectively. $E_{i,e}$ represents the annual emission of REE element e from production unit i. A_i is the activity intensity of the unit, represented by annual cement or clinker output, and $\bar{C}_e$ is the mean concentration of element e in cement-plant fine particulate matter. Element-specific $\bar{C}_e$ values were derived from the cement-plant PM-bound REE measurements reported by Yun et al. [3]. EF_i represents the fine particulate matter emission factor assigned to production unit i, expressed as $P_{i,j} \times (1 - \eta i,k)$, where $P_{i,j}$ is the pollution-generation coefficient for production section j and $\eta_{i,k}$ is the removal efficiency of end-of-pipe treatment technology k. Plant activity variables were obtained from the GCCT dataset, while PM generation factors and dust-control assumptions were assigned using published cement PM emission-factor measurements and cement-sector emission inventory studies [13-15, 21]. Element-specific emissions were then summed for each production unit and aggregated to national, regional and global levels. Country-level per-capita emissions were also calculated for the ecological health-correlation analysis. To

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reflect parameter uncertainty, emission estimates were propagated through the same calculation framework and summarized using the 2.5th, 50th and 97.5th percentiles. These values were used to report uncertainty intervals at the global, regional, national and elemental levels.

2.3. Driver analysis using Random Forest and SHAP

To identify the factors associated with spatial variation in cement-related REE emissions, a Random Forest (RF) model was developed using country-level emissions as the dependent variable. Explanatory variables included dust-removal performance, industrial output, total GDP, GDP per capita, plant type, majority cement type, alternative fuel use, clay calcination, and CCS/CCUS deployment. The RF model was selected because it can capture nonlinear relationships and interactions among predictors without imposing a priori linear assumptions [22, 23].

Shapley Additive explanations (SHAP) were then used to interpret the contribution of each predictor to the model output [24]. Mean absolute SHAP values were used to rank variable importance, while the sign and distribution of SHAP values were used to evaluate whether a variable tended to increase or decrease predicted emissions. Because SHAP reflects model attribution rather than direct causality, the results were interpreted as explanatory patterns rather than causal effects.

2.4. Health correlation and statistical analysis

To explore the potential public-health relevance of cement-related REE emissions, country-level per-capita REE emissions were correlated with the incidence and mortality of selected diseases, including ischemic heart disease, stroke, chronic obstructive pulmonary disease, lower respiratory infections, neonatal disorders, Alzheimer's disease, lung cancer, diabetes mellitus, and chronic kidney disease. Correlation analysis was conducted using Pearson's correlation coefficients, depending on data distribution. The resulting coefficients were visualized using correlation matrices.

All statistical analyses were conducted in Origin and Rstudio. Differences and associations were considered statistically significant at $p < 0.05$, unless otherwise stated. Because the health analysis was performed at the country level, the results were interpreted as ecological correlations rather than causal associations at the individual level.

2.5. Scenario analysis

To examine mitigation leverage points in the unit-level inventory, we developed three independent screening scenarios using the baseline inventory as the reference condition. The scenarios represented three policy-relevant pathways in the cement sector: material substitution, end-of-pipe particulate control and production-structure adjustment.

Scenario 1 (S1) represented a low-clinker cement pathway, in which clinker-related activity in large production units was adjusted according to the near-term clinker-reduction milestone in the IEA Net Zero pathway. This scenario reflects the role of clinker substitution and supplementary cementitious materials in reducing the environmental burden of cement production [25-27]. Scenario 2 (S2) represented a dust-control upgrade pathway, in which production units with lower particulate-control performance were assigned high-efficiency dust-removal technology, such as fabric filters, hybrid filters or wet electrostatic precipitators. Because the REEs quantified here are PM-bound, this scenario isolates the mitigation potential of improved particle capture [28, 29]. Scenario 3 (S3) represented a production-structure adjustment pathway, in which small-scale production units were phased out from the inventory to represent the retirement of small or outdated capacity [30-32].

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3. Results and discussion

3.1. Total REE emission burden from cement sector

The global cement sector emitted 248 t of REEs, with a 95% uncertainty interval of 44.3–739.0 t. The wide interval mainly reflects uncertainties in PM emission factors, dust-removal efficiencies and PM-bound REE concentration profiles derived from limited measured samples [3, 14, 15, 21]. Although these uncertainties affect the absolute magnitude of the estimates, the mean results still show a clear spatial concentration across regions and countries (Figures 1a and 2a). Asia-Pacific accounted for 69.4% of global cement-related REE emissions, followed by Africa at 20.6%, while the Americas and Europe contributed 6.0% and 4.0%, respectively. This pattern reflects the concentration of cement production and infrastructure demand in major cement-consuming regions [6-8, 21].

At the national scale, China and India were the two largest emitters, with total REE emissions of 59 t and 47 t, respectively, followed by Egypt at 11 t (Figure 1a). The uncertainty analysis showed a similar concentration: China, India and Egypt had the largest absolute uncertainty ranges, with 95% uncertainty-interval widths of 174.9 t, 123.4 t and 27.2 t, respectively (Figure 1b). This indicates that the countries contributing most to total emissions are also the main sources of uncertainty in the global estimate. The concentration of both emissions and uncertainty in the same countries suggests that future refinements should focus first on major cement-producing economies, where improved plant-level activity data, measured REE profiles and dust-removal information would have the greatest effect on the global inventory [3, 14, 15, 21].

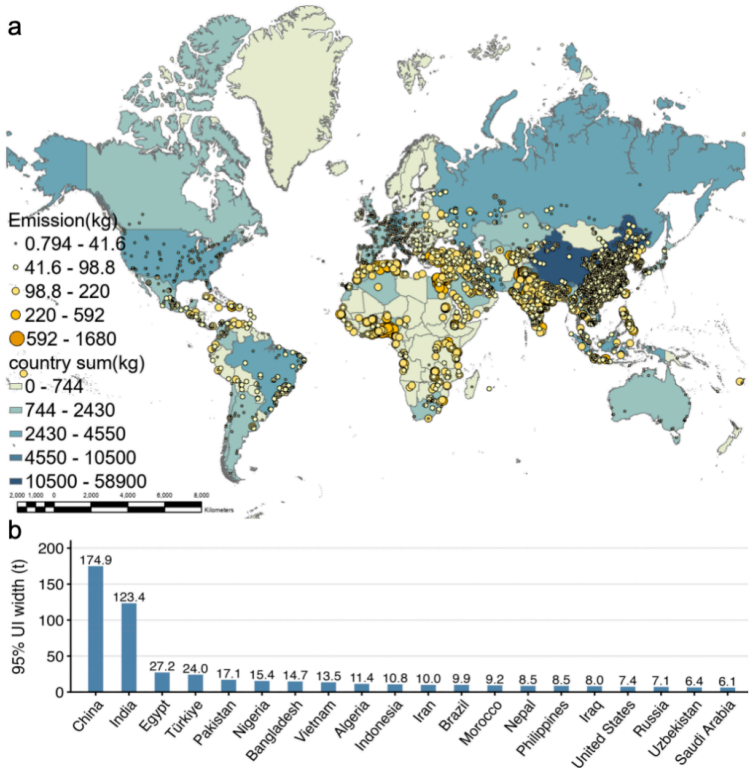


Figure 1. Global distribution and uncertainty of cement-related REE emissions. a, Country-level totals and plant-level emission points. b, Top 20 countries ranked by the width of the 95% uncertainty interval for national REE emissions. REEs, rare earth elements; UI, uncertainty interval

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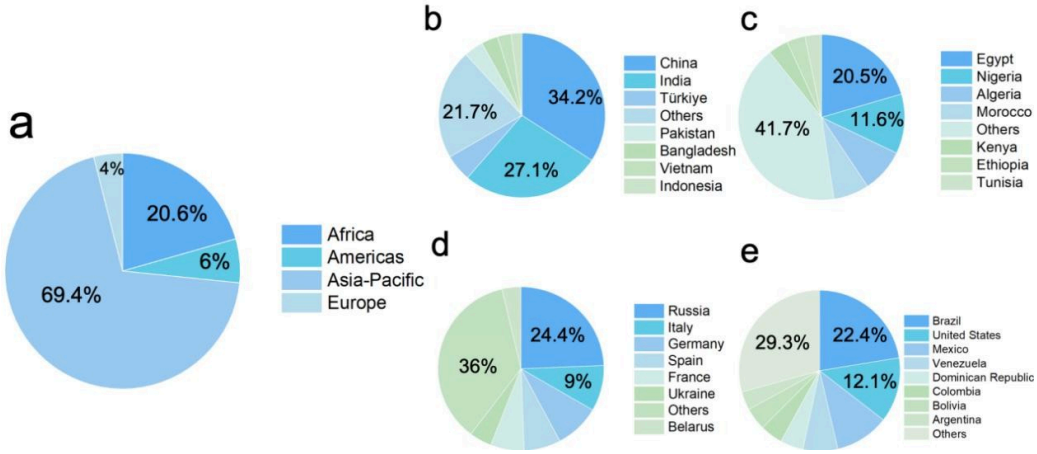


Figure 2. Regional and national contributions to cement-related REE emissions. a, Regional shares of global cement-related REE emissions. b–e, Country-level contributions within Asia-Pacific, Africa, Europe and the Americas. Asia-Pacific dominates the global total, while regional burdens are mainly controlled by a small number of high-emitting countries

A clear contrast was also observed between developing and developed countries. Developing countries contributed 225 t, representing 90% of global cement-related REE emissions, whereas developed countries contributed 22.8 t, or 10%. Country-level emissions in developing countries spanned a much wider and higher range than those in developed countries. This difference reflects the amount of cement production, infrastructure demand, and industrial expansion in developing economies [6-8]. From a mitigation perspective, these results indicate that REE emission control in the cement sector should prioritize high-output developing countries, especially those where large cement production is combined with uneven particulate-control capacity [14, 15, 21]. More importantly, these patterns reflect absolute emission burdens rather than emission intensities per unit of cement or clinker production. Therefore, countries with the highest total emissions are not necessarily those with the highest unit-level emission intensity, and future work should further distinguish scale effects from technology- or efficiency-related differences.

3.2. Elemental composition and spatial distribution of dominant REEs

The elemental composition of cement-related REE emissions was dominated by a small number of elements. Ce was the largest contributor, accounting for 38.5% of total REE emissions, followed by La at 21.0%, Nd at 13.8%, and Y at 11.6% (Figure 3a). Based on the global total emission burden, these shares correspond to 95 t Ce, 52 t La, 34 t Nd, and 29 t Y. Together, these four elements accounted for nearly 85% of total REE emissions. This indicates a strongly concentrated elemental composition, with the overall REE burden dominated by Ce, La, Nd, and Y rather than being evenly distributed across individual elements. The dominance of Ce, La and Nd is consistent with the light-REE-rich characteristics of clay- and shale-bearing raw materials used in cement production [2, 26, 33]. Cement raw materials such as limestone, clay, shale, and other mineral additives can contain naturally occurring REEs, and these elements may be released with particulate matter during high-temperature processing and clinker production [2, 3, 33]. The higher contribution of light REEs therefore likely reflects the geochemical composition of source materials, together with the particulate-bound nature of cement-sector emissions. Previous geochemical studies have also shown that light REEs are commonly enriched relative to heavy REEs in sedimentary material systems

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[33], while industrial particulate sources can show source-specific REE profiles [3]. This suggests that the elemental composition of cement-related REE emissions is not random, but inherits the geochemical signature of mineral feedstocks and the partitioning behavior of REEs during thermal processing and particulate release.

Among the dominant elements, Ce deserves particular attention because it contributed the largest mass fraction. The high share of Ce means that total REE emissions from the cement sector were largely shaped by Ce emissions, both globally and nationally. This is also environmentally relevant because cerium-containing particles have been associated with respiratory and pulmonary effects in toxicological studies [1, 34, 35]. Therefore, evaluating cement-related REE emissions only by total mass may be insufficient. From an inventory perspective, the dominance of Ce means that it can serve as a representative element for understanding the overall spatial pattern of cement-related REE emissions. The spatial distribution of dominant REEs was broadly consistent with the distribution of total REE emissions. Taking Ce as the representative case, China emitted 22.7 t, followed by India at 18 t (Figure 3b–e). Together, these two countries accounted for 42.6% of global Ce emissions. Other major contributors included Egypt, Türkiye, Pakistan, Nigeria, Bangladesh, Vietnam, Algeria, Indonesia, and Morocco, with the top ten countries contributing 62.7% of global Ce emissions. In other words, the dominant REEs did not show strongly differentiated geographical distributions; instead, they were concentrated in the same major cement-producing countries. Thus, the key finding is not that each element has a distinct geography, but that the dominant REEs share a broadly similar spatial pattern shaped mainly by cement production scale, clinker output, and particulate-emission potential [14, 15, 21]. In this sense, spatial variation in dominant REE emissions appears to be driven more strongly by differences in production scale and emission-control conditions than by fundamentally different elemental source regions.

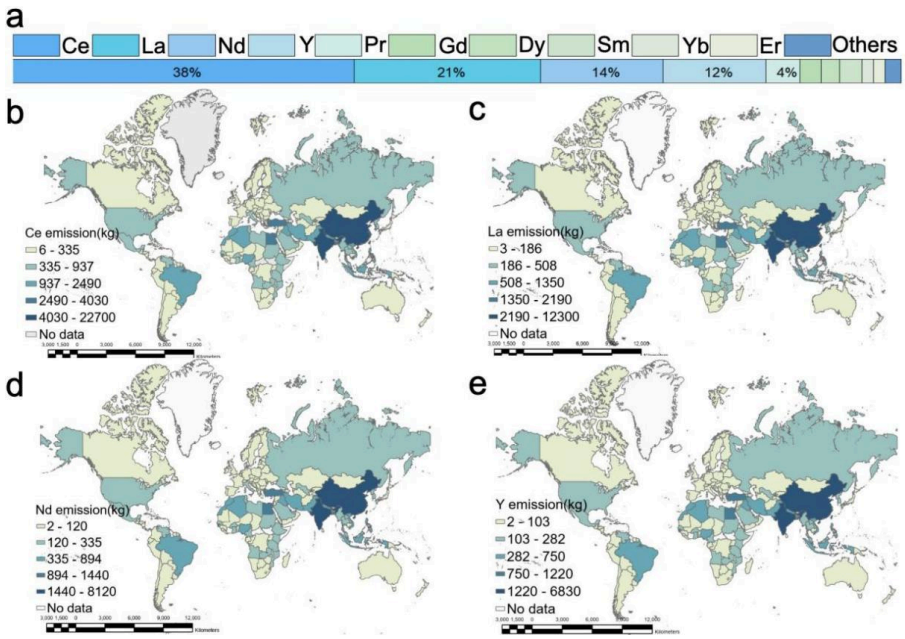


Figure 3. Elemental composition and spatial distribution of dominant REEs from the cement sector. a, Relative contributions of individual REEs to total cement-related emissions. b–e, Country-level emissions of the dominant elements, including Ce, La, Nd and Y. Ce is the largest contributor, while the main REEs show similar spatial patterns concentrated in high-output cement-producing countries

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3.3. Drivers of cement-related REE emissions at global and regional scales

The SHAP analysis was used to identify the main factors associated with spatial variation in cement-related REE emissions. Because SHAP values describe how each variable contributes to model predictions, the results should be interpreted as attribution patterns rather than direct causal effects [23, 24]. At the global scale, the leading explanatory factors included dust removal, industrial output, GDP-related variables, and selected low-carbon technology indicators (Figure 4a). These factors can be grouped into two categories: production-scale factors, which determine the potential amount of REE-bearing material generated, and technology or control factors, which influence the amount of particulate-bound REEs ultimately released to the atmosphere [14, 15, 21]. This suggests that cement-related REE emissions cannot be explained by production volume alone; they are shaped by the interaction between industrial activity and emission-control performance.

Regional patterns showed clear differences in the relative importance of these factors. In Asia-Pacific, dust removal was the dominant explanatory variable, followed by GDP per capita, total GDP, and industrial output (Figure 4b). This result indicates that in a region with very large cement production, differences in particulate-control systems and their operating performance strongly influenced national emission variation [14, 15, 21]. The broad SHAP distribution of dust removal also suggests that environmental-control capacity was uneven across countries and plant systems. Therefore, for Asia-Pacific, improving dust-removal efficiency, equipment maintenance, and plant-level emission management is likely to be a key near-term pathway for reducing cement-related REE emissions.

In Africa, the attribution pattern was different. Industrial output ranked first, followed by dust removal, total GDP, and GDP per capita (Figure 4c). This indicates that African cement-related REE emissions were more strongly associated with variation in production scale than with the current distribution of low-carbon technology deployment. The relatively low contribution of alternative fuel suggests that fuel substitution was not a major differentiating factor in the present regional pattern. For Africa, mitigation should therefore focus on controlling emissions from expanding cement production capacity, especially through improved particulate-control infrastructure and monitoring of high-output plants [6, 8, 21].

Europe and the Americas showed a broader attribution structure. Dust removal remained important, but alternative fuel and CCS/CCUS also contributed more visibly to the SHAP results (Figure 4d,e). This suggests that in regions with more diversified cement technologies, REE emission variation was associated not only with production scale and end-of-pipe control, but also with decarbonization-related process changes [36, 37]. In Europe, the relatively high contribution of CCS/CCUS should not be interpreted as a direct control effect on REE emissions; rather, it may reflect broader technological transitions occurring in plants adopting carbon-management measures. Overall, these results show that REE mitigation strategies should be region-specific. In Asia-Pacific and Africa, the priority should be dust-removal performance and control of emissions from high-output facilities. In Europe and the Americas, REE control should be considered together with alternative fuels, CCS/CCUS, and other low-carbon transition measures. Thus, cement-related REE mitigation is not a uniform global problem, but one shaped by regional differences in production structure, control technology, and industrial transition pathways.

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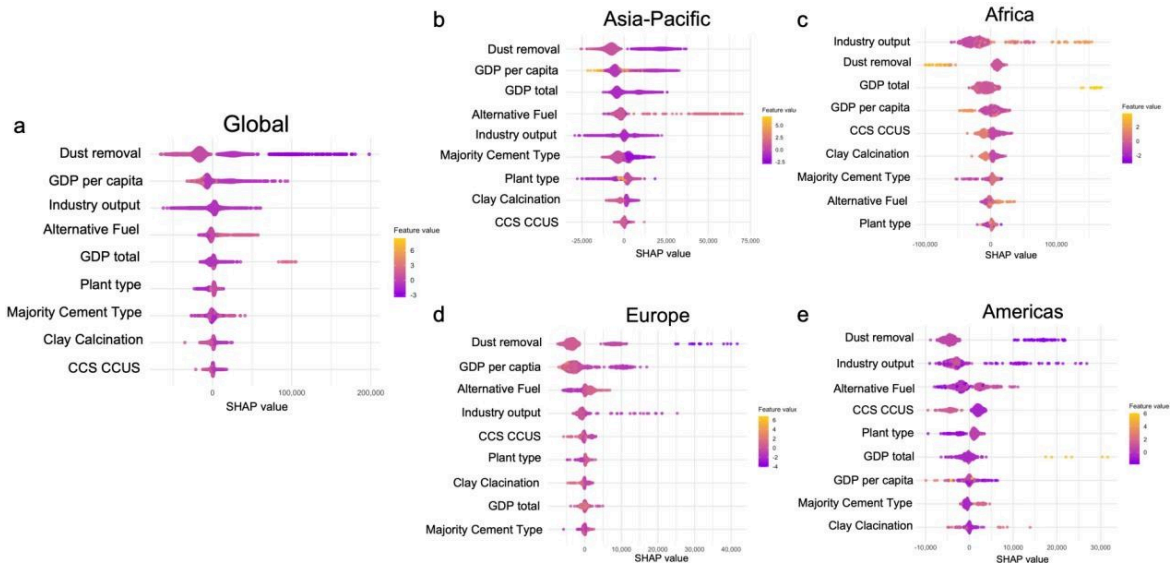


Figure 4. SHAP-based attribution of cement-related REE emission drivers. a, Global SHAP results for the random forest model. b–e, Regional SHAP results for Asia-Pacific, Africa, Europe and the Americas. Dust removal, industrial output, GDP-related variables and low-carbon technology indicators explain most spatial variation in predicted REE emissions. SHAP, Shapley additive explanations

3.4. Associations between per-capita cement-related REE emissions and disease burden

To examine whether cement-related REE emissions have any broad public-health signal at the national scale, country-level per-capita emissions were compared with incidence and mortality for selected high-burden diseases (Figure 5). These endpoints were obtained from the GBD country-level disease data and were used only for ecological screening rather than individual-level exposure assessment [20]. This comparison is relevant because cement production is an important source of PM-bound REEs [3], and particulate exposure has been linked to cardiovascular, respiratory and metabolic disease burdens in previous population-level studies [38-40]. Inhaled REE-bearing particles may also contribute to oxidative stress, inflammatory responses, DNA damage and pulmonary effects, although toxicological evidence varies across elements, particle forms and exposure routes [1, 35]. Therefore, the analysis was designed as an exploratory screen to place the emission inventory in a public-health context, rather than to infer disease causation.

The correlation results showed no strong association between national per-capita cement-related REE emissions and the selected disease endpoints. Diabetes mellitus showed the clearest positive correlation for both incidence and mortality, but the coefficients were small ($r = 0.26$ and 0.24, respectively). This weak positive signal may reflect the co-occurrence of cement-related industrial activity with broader urbanisation, industrialisation and metabolic-disease transitions, rather than a direct REE-specific effect [6-8, 41]. Lung cancer and Alzheimer's disease showed weak negative correlations, with $r = -0.26$ and -0.25 for incidence and $r = -0.25$ and -0.26 for mortality, respectively. These diseases are strongly affected by age structure, disease ascertainment, smoking, occupational exposures, healthcare access and other established risk factors that cannot be resolved using country-level emission indicators alone [41, 42]. National per-capita emissions are also a coarse exposure proxy because they do not capture the spatial distribution of exposed populations, particle size, chemical form, bioavailability, atmospheric transport or multi-source PM exposure [1,

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2, 35]. Thus, Figure 5 should be interpreted as preliminary ecological evidence: it suggests that cement-related REE emissions can be linked to public-health datasets for screening purposes, but it does not establish exposure, dose-response relationships or causal health effects.

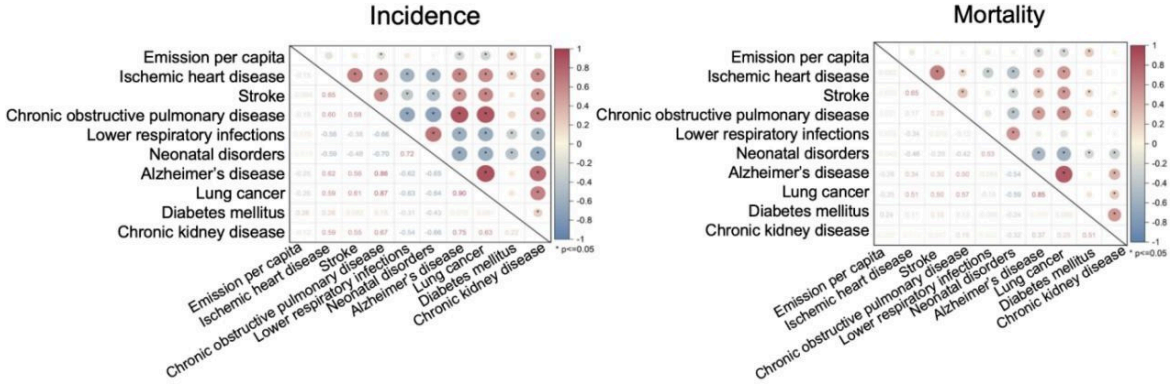


Figure 5. Correlations between per-capita cement-related REE emissions and disease burden. Correlation matrices showing the relationships between country-level per-capita cement-related REE emissions and disease incidence and mortality. The left panel shows incidence correlations, and the right panel shows mortality correlations. Circle colour and size represent the direction and strength of Pearson correlation coefficients, with red indicating positive correlations and blue indicating negative correlations. Asterisks indicate statistical significance

3.5. Emission-reduction potential under mitigation scenarios

The scenario analysis showed that all three mitigation pathways reduced global PM-bound REE emissions (Figure 6a). Emissions decreased from 247.9 t in the baseline inventory to 233.8 t under S1, 124.4 t under S2 and 230.3 t under S3, corresponding to reductions of 5.7%, 49.8% and 7.1%, respectively. The much larger reduction under S2 indicates that the main near-term mitigation leverage lies in particulate capture. This occurs because PM-bound REE emissions are directly controlled by the fraction of particles escaping dust-removal systems, and units assigned to lower-efficiency particulate control accounted for 149.4 t of baseline emissions. Upgrading these units therefore removes a large part of the remaining controllable emission burden, consistent with cement-sector BAT guidance and evidence from cement-manufacturing modernization showing that high-efficiency dust collectors can substantially reduce particulate-related impacts [28, 29].

The contrast among the scenarios indicates that PM-bound REE mitigation is governed by two interacting factors: emission scale and control gap. S1 mainly follows the distribution of large clinker-producing units, so its absolute reductions are concentrated in China and India, where cement production and clinker-related activity dominate the global total (Figure 6c; [4, 43]). S2 targets a remaining control gap, explaining why India, Egypt, Türkiye, Nigeria, Pakistan and Bangladesh show large reductions under this scenario (Figure 6c). Their mitigation potential reflects the overlap between high baseline emissions and lower particulate-control performance. By contrast, S3 identifies countries where small-scale units make a meaningful contribution to national emissions, showing a more structurally specific reduction pattern.

The regional results further show that mitigation priorities differ across cement-producing regions (Figure 6b). Asia-Pacific contributed the largest absolute reduction because of its large production base and high baseline emissions. Africa showed a strong response to S2 because lower-efficiency particulate-control units dominate its regional baseline, while broader studies project rapid growth in African combustion-related emissions, making early dust-control upgrading important for avoiding

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future emission lock-in [44]. This suggests that BAT-based dust standards, monitoring and enforcement would be especially relevant where cement capacity is expanding or control performance remains uneven [28, 45]. In comparison, S3 is best interpreted as a targeted structural measure, most useful where small or outdated units account for a meaningful share of emissions. This interpretation is consistent with evidence that industrial restructuring and phase-out policies can reduce air-pollution burdens when focused on inefficient capacity [31, 32]. Together, Figure 6a–c show that scenario analysis can screen where different mitigation measures are most relevant: production scale in Asia-Pacific, dust-control gaps in Africa and structural fragmentation in selected countries.

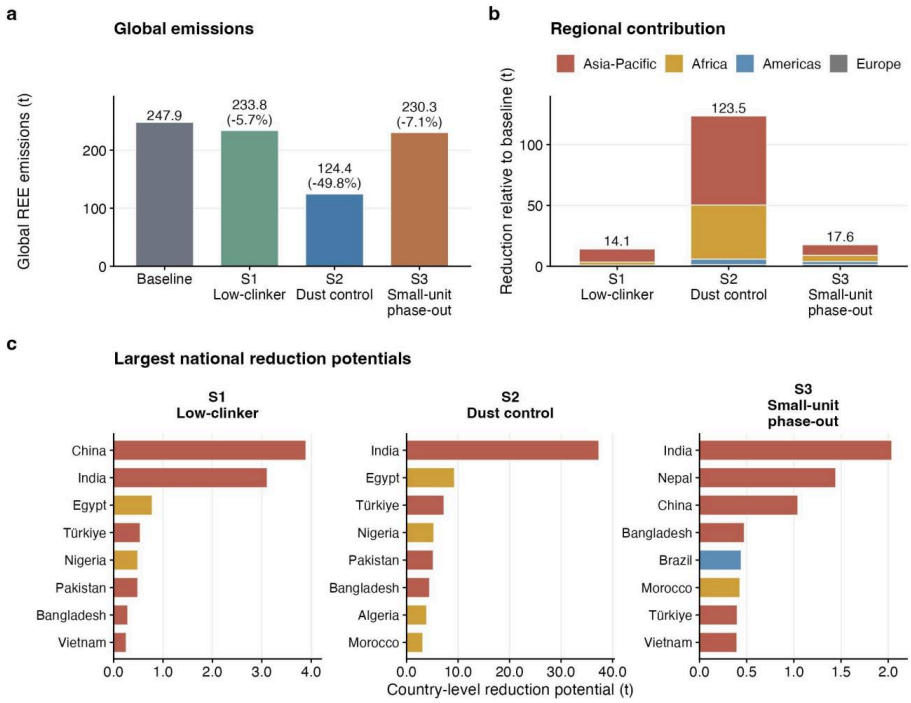


Figure 6. Mitigation potential of PM-bound REE emissions under three scenarios. a, Global emissions under the baseline and three scenarios: low-clinker cement production (S1), dust-control upgrading (S2) and small-unit phase-out (S3). Values show total emissions and percentage reductions from the baseline. b, Regional contributions to emission reductions relative to the baseline. c, Countries with the largest absolute reduction potentials under each scenario

4. Conclusion

This study presents the first global unit-level inventory of REE emissions from the cement industry, estimating a total of 248 t of REEs released annually with substantial regional concentration in Asia-Pacific and Africa. The elemental burden is dominated by Ce, La, Nd, and Y, reflecting the geochemical signature of cement raw materials. SHAP-based attribution reveals that dust-removal performance, industrial output, and GDP-related variables are the primary drivers of spatial emission variation, with distinct regional priorities. Scenario analysis demonstrates that dust-removal upgrading offers the largest near-term mitigation potential (49.8% reduction), providing a clear and actionable pathway for emission control. These findings establish a quantitative framework for understanding the industrial redistribution of geogenic trace elements through the cement sector and for identifying region-specific priorities for REE emission mitigation.

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Declaration of interest

The authors declare no competing interests.

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