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Life cycle assessment of three lighthouse cases representing distinct co-processing pathways in China's cement industry

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Abstract

As a resource- and energy-intensive industry and major source of greenhouse gas emissions, the cement industry is central to China’s carbon peaking and carbon neutrality goals. However, life cycle assessment using generic databases or industry-average inventories may obscure production-line differences. Data collected during 2021-2025 from three representative production lines were evaluated under a harmonized framework. The pathways involved using low-grade limestone and multiple industrial wastes as alternative raw materials and fuels, co-processing heavy metal-contaminated soil, and using municipal solid waste as an alternative fuel. Their integrated environmental load indicators were 16.63%, 17.68%, and 20.42% below the consistent reference scenario, respectively. The largest reductions occurred in abiotic depletion potential, human toxicity potential, and global warming potential, corresponding to resource-conservation, pollution-control, and fuel-substitution pathways. Environmental benefits and burden shifts depended on the substituted function and input properties. These findings provide production-line-level evidence for selecting and optimizing resource-recovery pathways in China’s cement industry.

Abbreviations

Abbreviations	Full name
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
IELI	Integrated environmental load indicator
ADP	Abiotic depletion potential
GWP	Global warming potential
HTP	Human toxicity potential
AP	Acidification potential
POCP	Photochemical oxidation potential
EP	Eutrophication potential
LU	Land use
AHP	Analytic hierarchy process
CUCC-NY	Nanyang China United Cement Co., Ltd.
CUCC-XZ	Xuzhou China United Cement Co., Ltd.
CRC-TY	China Resources Cement (Tianyang) Co., Ltd.
USGS	U.S. Geological Survey
NRA	National Railway Administration of the People’s Republic of China

Introduction

China is by far the world's largest cement producer. In 2025, its cement output was estimated at 1.70 Gt, accounting for approximately 44.7% of the global total of 3.80 Gt [1]. Given this production scale, improvements in the environmental performance of China's cement industry are important not only for achieving national carbon peaking and carbon neutrality goals but also for global industrial decarbonization. Cement production is highly energy- and resource-intensive, with substantial greenhouse gas emissions arising from fuel combustion and carbonate decomposition [2]. As conventional energy-efficiency measures gradually approach their technical limits, emission-reduction efforts in the sector are shifting towards integrated pathways involving reductions in the clinker factor [3, 4], the use of alternative raw materials and fuels [5, 6], process electrification [7, 8], and carbon capture [9, 10]. In China's cement industry, production scale, energy efficiency, and process equipment vary across enterprises and regions, resulting in substantial differences in the energy-saving, carbon-reduction, and pollution-abatement effects of the same technology [11, 12]. Therefore, the assessment of resource-recovery technologies should not be limited to their average carbon-reduction potential but also examine how they alter resource inputs, energy consumption, and multiple environmental impacts during production.

Life cycle assessment (LCA) comprehensively identifies all inputs to and outputs from a product system throughout its life cycle and quantitatively evaluates their associated environmental burdens on the natural environment, human health, and resource consumption [13]. However, existing LCA studies of the cement industry generally rely on generic databases, industry-average inventories, or literature data, which have limitations in terms of representativeness and transparency [14]. Moreover, the temporal, geographical, and technological relevance of the data directly affects the reliability of the resulting conclusions [15]. Recent plant-level studies have confirmed appreciable differences among production lines in emission factors, raw material and fuel characteristics, and pollution-control performance [12, 16, 17]. Consequently,

differences among innovative technological pathways in raw material formulations, heat consumption, electricity consumption, waste composition, and emission-control performance may be obscured by averaging if only generic data are used. A localized cement LCA therefore requires primary foreground inventories that reflect the actual raw materials, energy mix and pollutant emissions of the production lines being evaluated.

Despite this need, much of the available evidence on individual resource-recovery technologies is still derived from laboratory experiments, including investigations of industrial by-product utilization [18], fuel substitution [19], and pollutant co-processing [20]. Although such studies are valuable for identifying reaction mechanisms and demonstrating technical feasibility, they cannot fully capture the heterogeneity of cement production in China. Over the past five years, studies based on actual cement-plant or production-line data have been conducted in India [21], Saudi Arabia [22], Denmark [23], and the United States [24]. These studies demonstrate the importance of operating records for representing actual production conditions. However, not all of these studies are full LCA researches and generally focus on a single technology, process or environmental issue. Comparative LCA researches in cement production based on operating data under a harmonized methodological framework still remain limited.

To address this methodological and empirical gap, field investigations and operational data collection covering Chinese cement production lines were conducted from 2021 to 2025. A structured dataset containing more than 60000 records on raw material and fuel inputs, energy consumption, product output and pollutant emissions was compiled. Based on the preceding work, three operating new dry-process cement production lines were selected as representative cases of three distinct resource-recovery pathways. CUCC-NY represents a resource-conservation pathway through the use of low-grade limestone and multiple industrial wastes as alternative raw materials and fuels. The analysis draws on its 2024 operational data. CUCC-XZ represents a pollution-control pathway through the co-processing of heavy metal-contaminated soil in its cement kiln. The analysis draws on its operational data from

2021 to 2023. And CRC-TY represents a fuel-substitution pathway through the use of municipal solid waste as an alternative fuel. The analysis draws on its operational data from 2021 to 2024. This study compares seven environmental impact categories and IELI to identify the principal environmental benefits, burden shifts, and production hotspots of each production line, and ultimately elucidates the underlying causes of the differences in environmental benefits.

Results

LCA results for the three production lines

LCA calculations were performed for the conventional cement and the cement products from the three production lines. The results are summarized in Table 1.

Cements from all three production lines exhibited lower IELI than the conventional cement. The IELI value was 4.75×10^{-12} for the conventional cement, compared with 3.96×10^{-12}, 3.91×10^{-12}, and 3.78×10^{-12} for CUCC-NY, CUCC-XZ, and CRC-TY, respectively. The IELI corresponded to reductions of 16.63%, 17.68%, and 20.42%, respectively, as shown in Fig. 1 (a).

Table 1. LCA accounting results for various production lines.

Calculation categories	Environmental categories	P·O 42.5	CUCC-NY	CUCC-XZ	CRC-TY
Characterization results	ADP	1.01×10^{-2}	3.02×10^{-3}	5.10×10^{-3}	5.89×10^{-3}
	GWP	6.52×10^{2}	6.02×10^{2}	5.96×10^{2}	5.09×10^{2}
	HTP	1.25×10^{0}	6.07×10^{-1}	7.46×10^{-2}	3.82×10^{0}
	AP	8.74×10^{-1}	6.50×10^{-2}	8.64×10^{-2}	2.20×10^{-1}
	POCP	3.93×10^{-2}	1.96×10^{-3}	3.00×10^{-3}	8.29×10^{-3}
	EP	5.28×10^{-2}	1.03×10^{-2}	1.34×10^{-2}	3.58×10^{-2}
	LU	1.92×10^{-2}	1.27×10^{-2}	1.16×10^{-2}	2.01×10^{-3}
Normalization results	ADP	4.70×10^{-13}	1.41×10^{-13}	2.38×10^{-13}	2.75×10^{-13}
	GWP	1.56×10^{-11}	1.44×10^{-11}	1.43×10^{-11}	1.22×10^{-11}

	HTP	4.84×10^{-13}	2.35×10^{-13}	2.89×10^{-14}	1.48×10^{-12}
	AP	3.66×10^{-12}	2.72×10^{-13}	3.62×10^{-13}	9.21×10^{-13}
	POCP	1.07×10^{-12}	5.33×10^{-14}	8.15×10^{-14}	2.25×10^{-13}
	EP	3.34×10^{-13}	6.54×10^{-14}	8.48×10^{-14}	2.27×10^{-13}
	LU	1.66×10^{-17}	1.10×10^{-17}	9.96×10^{-18}	1.73×10^{-18}
IELI		4.75×10^{-12}	3.96×10^{-12}	3.91×10^{-12}	3.78×10^{-12}

Differential responses across environmental impact categories

Fig. 1 (b) shows the changes in seven environmental impact categories for cement products from the three production lines relative to conventional cement.

At CUCC-NY, the normalized ADP value was 3.29×10^{-13} lower than that of the conventional cement, corresponding to a reduction of 70.00%, the largest ADP reduction among the three production lines. The normalized values of GWP, HTP, AP, POCP, EP, and LU decreased by 7.69%, 51.45%, 92.57%, 95.02%, 80.42%, and 33.73%, respectively. The pronounced reduction in ADP was consistent with the use of low-grade limestone, converter slag, sulfuric acid residue, and fly ash as alternative raw materials, as well as textile waste and carbon black as alternative fuels.

At CUCC-XZ, the normalized HTP value was 4.55×10^{-13} lower than that of the conventional cement, corresponding to a reduction of 94.03%, the largest HTP reduction among the three production lines. The normalized values of ADP, GWP, AP, POCP, EP, and LU decreased by 49.36%, 8.33%, 90.11%, 92.38%, 74.61%, and 40.00%, respectively. This production line uses furnace slag and coal gangue as alternative raw materials and co-processes heavy metal-contaminated soil at a dosage equivalent to approximately 3% of the clinker mass. This combination of raw material substitution and contaminated-soil co-processing is consistent with the particularly pronounced reduction in HTP.

At CRC-TY, the normalized GWP value was 3.42×10^{-12} lower than that of the conventional cement, corresponding to a reduction of 21.79%, the largest GWP reduction among the three production lines. The normalized values of ADP, AP, POCP, EP, and LU decreased by 41.49%, 74.84%, 78.97%, 32.04%, and 89.58%,

respectively. This production line uses fly ash and coal boiler slag as alternative raw materials and municipal solid waste as an alternative fuel. However, its normalized HTP value was 9.96×10^{-13} higher than that of the conventional cement, corresponding to an increase of 205.79%. Overall, all environmental impact categories were lower than the corresponding reference values for the three production lines, with the sole exception of HTP at CRC-TY.

Composition of IELI

The composition of IELI for the conventional cement production line and the three representative production lines is shown in Fig. 1 (c). GWP was the largest contributor to IELI in all four cases, accounting for 87.46% in conventional cement production line, and 96.84%, 97.39%, and 85.95% at CUCC-NY, CUCC-XZ, and CRC-TY, respectively. Although ADP was assigned a higher weight coefficient than GWP, its normalized value was very low. Consequently, its contribution to IELI was substantially smaller than that of GWP. HTP accounted for 2.55% of IELI in conventional cement production line, and 1.48%, 0.18% at CUCC-NY and CUCC-XZ, respectively. By contrast, its contribution at CRC-TY was markedly higher, reaching 9.80%, indicating that a reduction in IELI does not necessarily imply that toxic impacts are negligible. The remaining four impact categories made minor contributions to IELI at all three representative production lines.

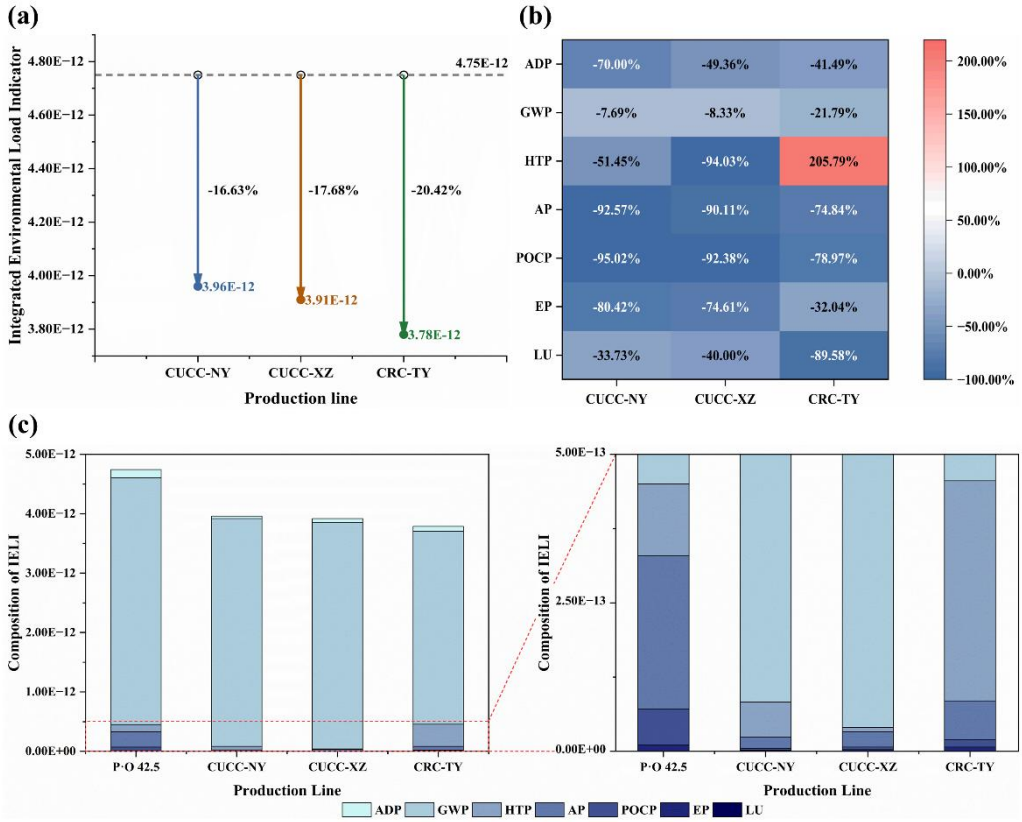


Fig. 1. Integrated environmental load indicator and pathway-specific environmental responses. (a) Reduction rate compared with conventional cement for three representative production lines; (b) Changes in seven environmental categories of cement from three representative production lines compared to conventional cement; (c) IELI composition of cement.

Production stage hotspots

Production stage analysis further traces the overall changes across the three production lines to specific production processes. Fig. 2 presents the contributions of raw material grinding, clinker calcination, and cement grinding to the environmental impacts of cement production.

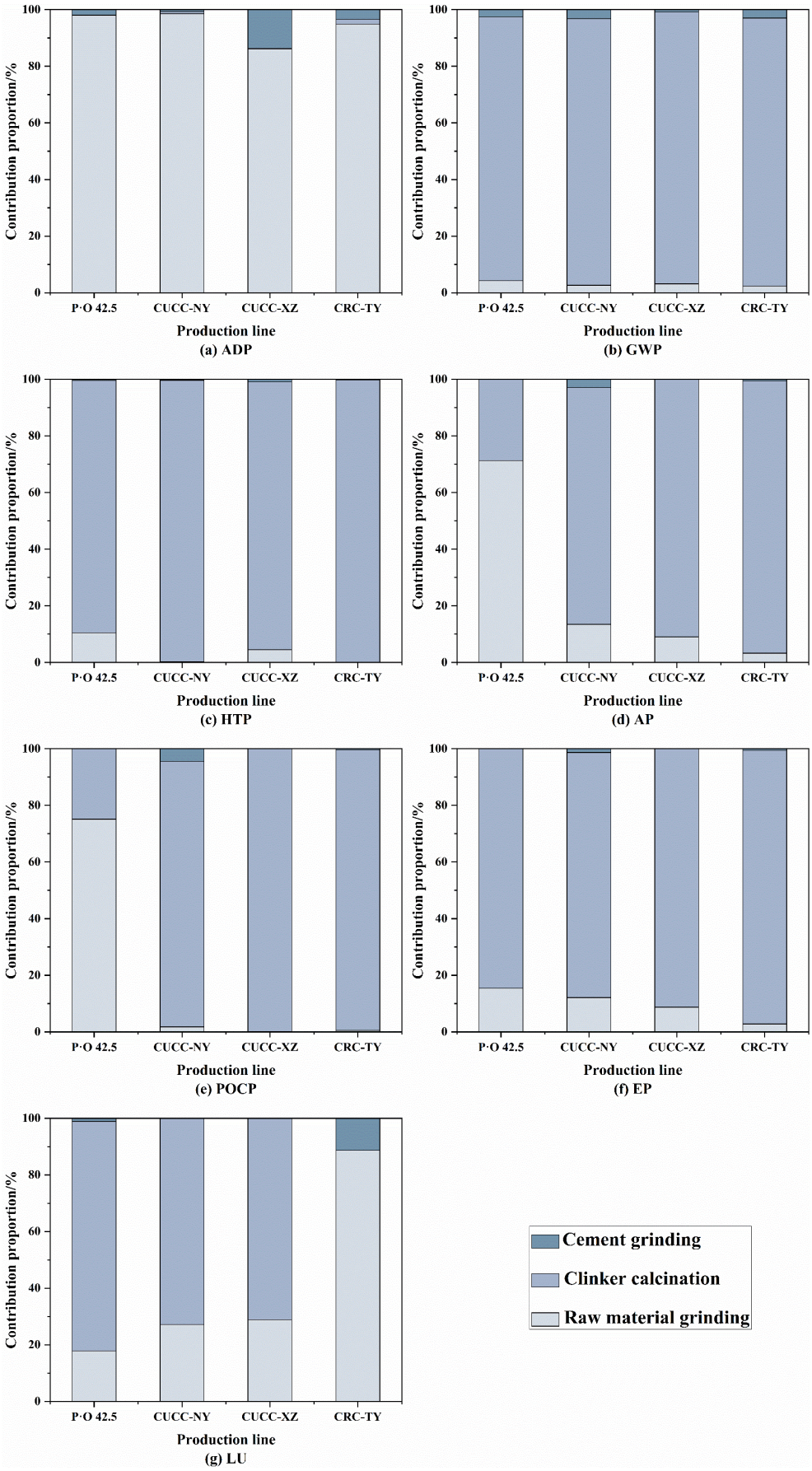


Fig. 2. Production stage contribution profiles across environmental categories.

Raw material grinding dominated ADP in all four cases, accounting for 98.02%, 98.54%, 86.17%, and 94.87% in the reference scenario, CUCC-NY, CUCC-XZ, and CRC-TY, respectively. This dominance arose because the burdens assigned to this stage included raw material supply, encompassing limestone consumption and the non-renewable resources consumed during extraction and transportation, such as coal and petroleum. At CUCC-XZ, the contribution of cement grinding to ADP was markedly higher than in the other cases because of the input of alternative constituents, including slag, gypsum, and mineral powder.

Clinker calcination overwhelmingly dominated GWP in all four cases, accounting for 93.17%, 94.15%, 95.96%, and 94.66% in the reference scenario, CUCC-NY, CUCC-XZ, and CRC-TY, respectively. These results demonstrate that clinker calcination remained the principal hotspot in climate impact. Although the three innovative technological pathways reduced GWP, they did not alter this underlying hotspot structure. It was associated with carbonate decomposition, fuel combustion, and electricity consumption [25].

Clinker calcination also dominated HTP, accounting for 89.10%, 99.44%, 94.58%, and 99.81% in the reference scenario, CUCC-NY, CUCC-XZ, and CRC-TY, respectively. HTP decreased at CUCC-NY and CUCC-XZ but increased at CRC-TY. The increase at CRC-TY was primarily associated with the use of municipal solid waste as an alternative fuel during clinker calcination. However, the underlying causes require further examination in relation to the composition, moisture content, lower heating value, and pretreatment of the municipal solid waste.

At all three production lines, clinker calcination also dominated AP, POCP, and EP because this stage was associated with substantial emissions of pollutants such as sulfur dioxide, nitrogen oxides, and fluoride compounds. The stage distribution of LU differed considerably. Clinker calcination accounted for a relatively large share at CUCC-NY and CUCC-XZ, whereas raw material grinding accounted for a larger share at CRC-TY. However, owing to its smallest weight coefficient, its contribution to IELI is negligible.

Discussion

Although all three innovative pathways reduced IELI, they operated through different mechanisms because each served a distinct substitution function. CUCC-NY, CUCC-XZ, and CRC-TY achieved their most pronounced reductions in ADP, HTP, and GWP, respectively, indicating primary advantages in conserving non-renewable resources, reducing human toxicity potential, and mitigating climate impacts. These responses correspond directly to the core substitution function of each pathway: the displacement of multiple non-renewable resources by diverse industrial solid wastes at CUCC-NY; the combined functions of raw material substitution and pollution remediation through the co-processing of heavy metal-contaminated soil at CUCC-XZ; and the displacement of fossil fuels by municipal solid waste at CRC-TY. Accordingly, the three production lines can be characterized as resource-conservation, pollution-control, and fuel-substitution pathways.

These cases further demonstrate that reduction in IELI reflects the combined balance among three components: (1) the avoided burdens associated with conventional non-renewable raw material and fuel inputs; (2) the additional burdens arising from waste treatment, transportation, and related processes; (3) the changes in energy consumption and emissions after the alternative materials are introduced into the cement kiln. At CUCC-NY, the reduction in IELI arose primarily from the first component. Higher substitution rates of alternative raw materials and fuels reduced the consumption of non-renewable resources such as limestone and coal, as well as pollutant emissions linked to limestone extraction. This is consistent with the general LCA mechanism whereby industrial by-products and solid wastes displace conventional raw materials and fuels, thereby reducing the demand for clinker and natural minerals [3, 26, 27]. At CUCC-XZ, the environmental benefits arose from both avoided raw material inputs and pollution remediation. The process simultaneously enabled the treatment and resource utilization of contaminated soil, helping to mitigate environmental contamination and potential long-term risks associated with hazardous wastes containing heavy metals. This conclusion is consistent with

previous findings [28]. At CRC-TY, the reduction in IELI depended more strongly on the balance between the benefits of fuel substitution and the additional burdens associated with waste treatment and changes in emissions. The partial substitution of fossil fuels with municipal solid waste reduced greenhouse gas emissions, demonstrating the potential climate benefits of alternative fuel utilization [29, 30]. However, the use of municipal solid waste as an alternative fuel also introduced additional pollutant sources, increasing potential risks associated with fluoride compounds and other pollutants.

The contrasting responses of CUCC-XZ and CRC-TY further indicate that the properties and multifunctionality of co-processed materials shape environmental trade-offs and the resulting burden shifts. CUCC-XZ treats contaminated soil characterized primarily by concentrations of cadmium, manganese and hydrargyrum above the relevant threshold values, whereas CRC-TY treats municipal solid waste with a substantially more complex composition. Although both materials are co-processed in cement kilns, they differ markedly in their material properties and substitution functions.

At CUCC-XZ, the contaminated soil partially substitutes for raw materials, while the cement kiln simultaneously provides a remediation function. Therefore, the LCA results depend on the treatment route that the contaminated soil would otherwise follow, the partitioning of metals among cement kiln dust, clinker, and cement, the leaching behavior of the cement products, and the allocation rules applied to the treatment function. Allocation approaches for by-products and wastes can also affect the results [31, 32]. Previous research has indicated that using contaminated soil as an alternative raw material has the potential to avoid raw material extraction, reduce environmental burdens, and lower treatment costs [28, 33]. Nevertheless, controls on total inputs, compliance with leaching limits, and long-term ecological safety must still be considered. A reduction in HTP should not be equated with the absence of long-term risk. At CRC-TY, the moisture content, lower heating value, and composition of municipal solid waste jointly determine the effective thermal substitution rate and emission result. The preceding calculations revealed divergent trends in GWP and

HTP, indicating that the climate benefits of fuel substitution can coexist with additional toxic burdens. Fuel properties, pretreatment energy consumption, and waste treatment routes can cause HTP to change differently from other environmental impact categories [34, 35]. Therefore, the increase in HTP should not be attributed simplistically to a single pollutant.

Despite the differences among the three pathways, clinker calcination remained overwhelmingly dominant across multiple environmental impact categories. Studies conducted in different national contexts have identified the thermal energy demand of clinker production, fuel combustion, and kiln emissions as the principal environmental hotspots of cement production [36, 37]. Accordingly, the three innovative pathways examined in this study primarily improved the input and emission profiles of the production lines rather than altering the structural hotspot associated with clinker calcination.

This structural constraint also explains why the resource-related, climate-related, and health-related indicators did not improve in parallel. Raw material substitution can reduce the demand for natural minerals and the associated upstream burdens. However, process-related CO_2 emissions still remain if neither the clinker factor nor carbonate decomposition is reduced. Alternative fuels can reduce emissions associated with fossil fuel combustion but cannot directly eliminate the CO_2 released through raw material decomposition. The co-processing of contaminated soil adds a pollution remediation function but does not reduce the thermal energy demand of clinker production. Recent cement decarbonization studies have similarly indicated that raw material or fuel substitution alone is insufficient to achieve deep emission reductions. It should be combined with reductions in clinker use, improvements in kiln thermal efficiency, and waste heat utilization [38, 39].

From an engineering perspective, the comparison of the three production lines should not be interpreted as a ranking of the three resource-recovery technologies. What can be transferred from these cases to other cement production lines is their substitution functions and control conditions, rather than the magnitude of IELI reduction of a particular enterprise. The environmental benefits of industrial by-

product substitution depend on the regional availability and supply stability of solid wastes, the chemical composition of the alternative materials, clinker quality requirements and transportation distances. The co-processing of contaminated soil requires clearly defined limits on heavy metal inputs, together with monitoring of kiln emissions and the long-term leaching behavior of cement products. The use of municipal solid waste as an alternative fuel requires simultaneous control of its moisture content, lower heating value, and pretreatment energy consumption.

Therefore, pathway selection should begin by identifying the intended function: substituting for natural minerals, providing pollution remediation or displacing fossil fuels. Then, the characteristics of locally available wastes, production line equipment, and pollution control capacity should be evaluated to determine whether the avoided burdens are sufficient to offset the additional burdens introduced by the pathway. Deployment decisions should simultaneously apply climate-related, resource-related, and toxicity-related criteria, thereby avoiding technology selection based solely on IELI or on a reduction in a single environmental impact category. This function-oriented decision logic is summarized in Fig. 3. At the industry level, resource-recovery measures should be implemented in conjunction with reductions in the clinker factor, improvements in kiln thermal efficiency, the use of low-carbon electricity, and strengthened pollutant emission controls. The three resource-recovery pathways can improve specific environmental objectives but cannot independently eliminate the structural environmental burdens associated with clinker calcination.

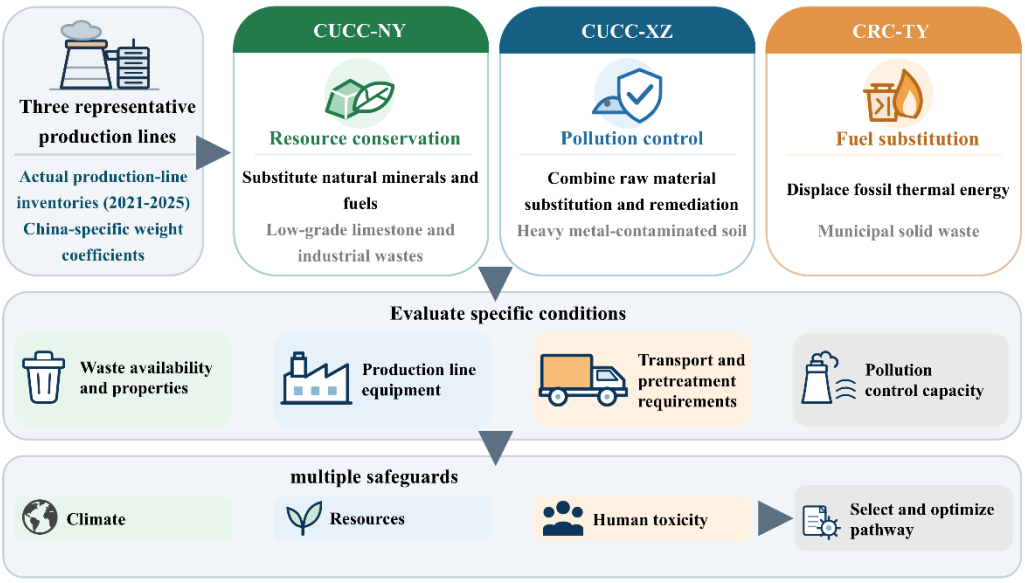


Fig. 3. Function-oriented selection of cement resource-recovery pathways.

To translate this decision framework into industrial practice, the assessment framework was operationalized as a digital tool for actual production line. Following data cleaning, unit harmonization, and process integration, the “Localized Database System for Full Life Cycle Environmental Loads of Cementitious Materials V1.0” (Fig. 4 (a)) was established. On this basis, the supporting software “Cement Full Life Cycle Assessment (LCA) System” (Fig. 4 (b)), was developed and applied at the participating production lines (Fig. 4 (c) and (d)). By linking actual operating data with harmonized allocation and impact assessment procedures, the system supports the identification of environmental hotspots and potential burden shifts. This industrial application converts production-line evidence into a repeatable workflow for environmental management and technology selection.

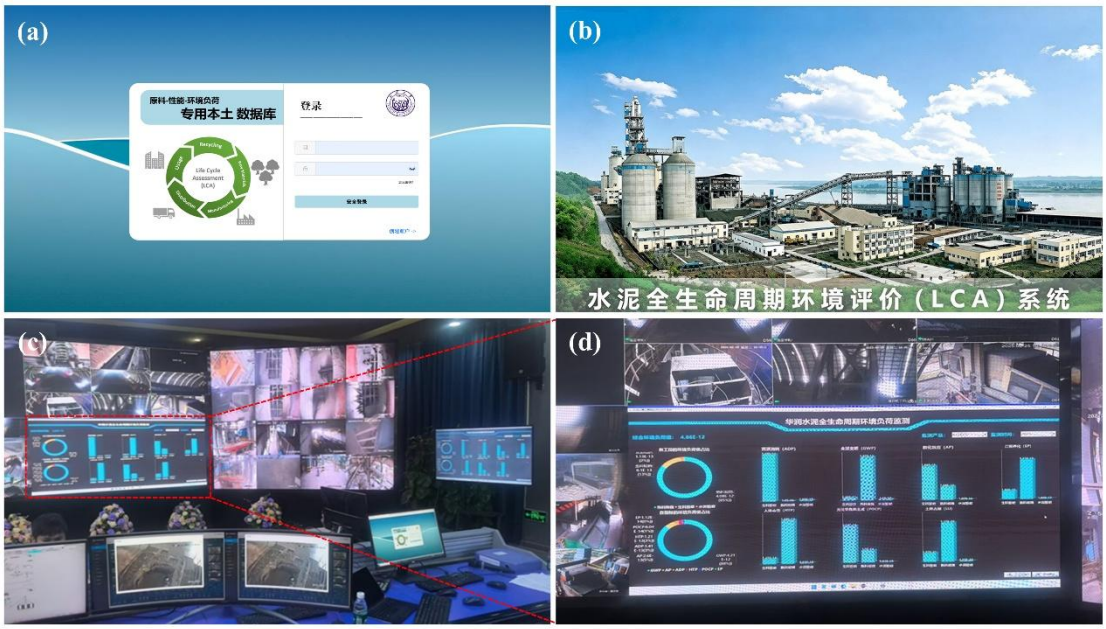


Fig. 4. Digital implementation of the assessment framework at an operating cement production line. (a) Login interface of the localized LCA database system; (b) The “Cement Full Life Cycle Assessment (LCA) System”; (c) Central control system of the cement production line; (d) Enlarged view of the dedicated LCA display.

Taken together, the cross-case analysis showed that the principal environmental benefit was associated with the substitution function, whereas environmental trade-offs and resulting burden shifts were shaped by the properties and multifunctionality of the co-processed materials. IELI provides a useful summary of overall environmental performance, but it must be interpreted alongside the results for all seven environmental impact categories and their production stage contributions. By linking a harmonized assessment framework with localized operating data and digital implementation, this study not only quantify changes in the IELI, but also provide an actionable basis for selecting and optimizing innovative technological pathways under different operating conditions.

Methods

According to ISO 14040 [13] and ISO 14044 [40], LCA comprises four phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and life cycle interpretation.

Goal and scope definition

The function unit and system boundary are defined according to the specific study context, providing the basis for subsequent analysis. In cement production, the system boundary is commonly defined as “cradle-to-gate” and encompasses raw material extraction, raw meal preparation, clinker calcination, cement preparation, and transportation processes [41], as shown in Fig. 5.

This study adopted “cradle-to-gate” system boundary, including the acquisition and transportation of conventional and alternative raw materials, necessary waste pretreatment, raw meal preparation, clinker calcination, cement grinding, the upstream production of fuels and electricity, and power generation from waste heat recovery. The functional unit is defined as 1t of cement, and P·O 42.5 cement is used as the reference for comparison.

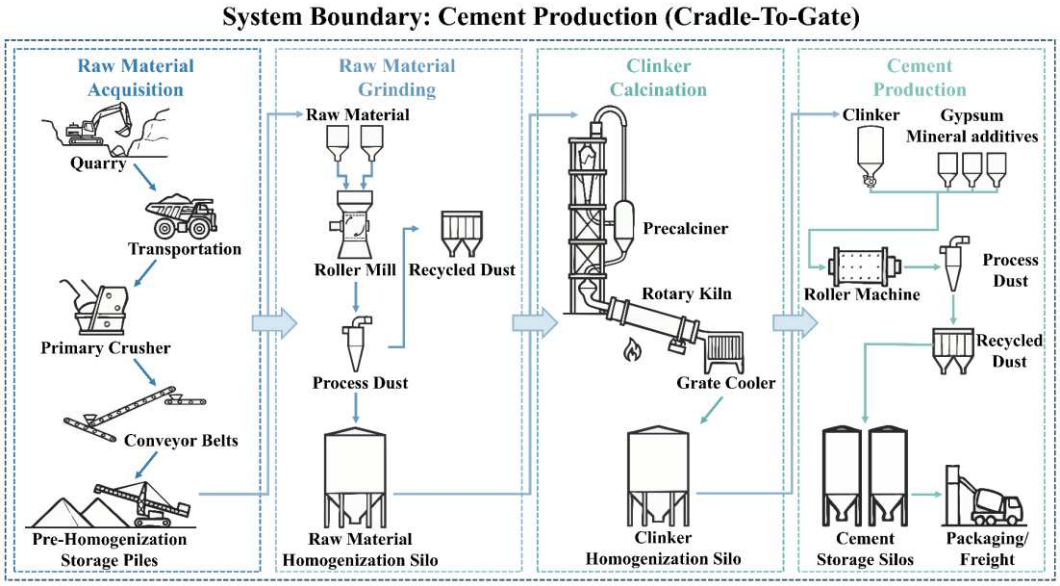


Fig. 5. System boundary of conventional cement production.

Life cycle inventory

LCI involves various input and output data throughout the entire life cycle. The data used in this study were obtained from the operational records of the three production lines and the results of independent third-party testing. Secondary data were used only for upstream processes that could not be obtained directly from plant operating records. Some data for the raw material extraction stage were obtained from the “Chinese Life Cycle Database (CLCD).” Missing parameters related to railway

transportation were supplemented using the 2021 Railway Statistical Bulletin [42] and the 2023 Railway Statistical Bulletin [43].

Life cycle impact assessment

LCIA involves compiling and calculating the input and output data, then qualitatively describing and quantitatively evaluating the magnitude and significance of environmental burdens throughout the life cycle. It mainly comprises three procedures: impact classification, characterization, normalization and weighting.

This study applies the CML2001 impact assessment method [44] and selects seven environmental impact categories for comprehensive assessment: abiotic depletion potential (ADP), global warming potential (GWP), human toxicity potential (HTP), acidification potential (AP), photochemical oxidation potential (POCP), eutrophication potential (EP), and land use (LU).

Characterization builds on impact classification and uses characterization factors (c_i) to quantify the contributions of different inventory items (Q_i) to a given environmental impact category. The characterization results for each category are then aggregated into an environmental load equivalent (E_x), calculated as follows:

$$E_x = \sum Q_i \times c_i \tag{1}$$

Due to environmental load equivalents are expressed in different units, normalization is required to enable comparison of their relative magnitudes. The normalized result is the dimensionless ratio of an environmental load equivalent (E_x) to its corresponding reference value ($E_{x,0}$). In this study, the global total equivalent for each environmental load is used as the normalization reference value [45].

To quantify the integrated environmental load of the system and enable comparisons among different systems, each normalized environmental load is assigned a weight coefficient (w_x) according to its relative importance. The weighted calculation yields the final assessment value, referred to as the integrated environmental load indicator (IELI). The IELI is calculated as follows:

$$IELI = \sum w_x \frac{E_x}{E_{x,0}}, \sum w_x = 1 \tag{2}$$

The weight coefficients used in this study were derived from our previous

research [46], in which the AHP was applied to questionnaire responses collected from experts in China's cement research and industrial communities.

The Base value of environmental load and weight coefficients are presented in Table 2.

Table 2. Base value of environmental load and weight coefficients.

Environmental impact categories	Equivalent unit	Base value	Weight coefficients
ADP	kg Sb eq.	2.14×10^{10}	0.3005
GWP	kg CO_2 eq.	4.18×10^{13}	0.2663
HTP	kg 1,4-dichlorobenzene eq.	2.58×10^{12}	0.2502
AP	kg SO_2 eq.	2.39×10^{11}	0.0704
POCP	kg ethylene eq.	3.68×10^{10}	0.0565
EP	kg PO_4^{3-}eq.	1.58×10^{11}	0.0326
LU	Net primary productivity	1.16×10^{15}	0.0235

Life cycle interpretation

IELI provides an overall measure of the environmental impacts throughout the material life cycle. During this phase, the assessment results for the individual life cycle stages are comprehensively analyzed. The LCA calculation structure is illustrated in Fig. 6.

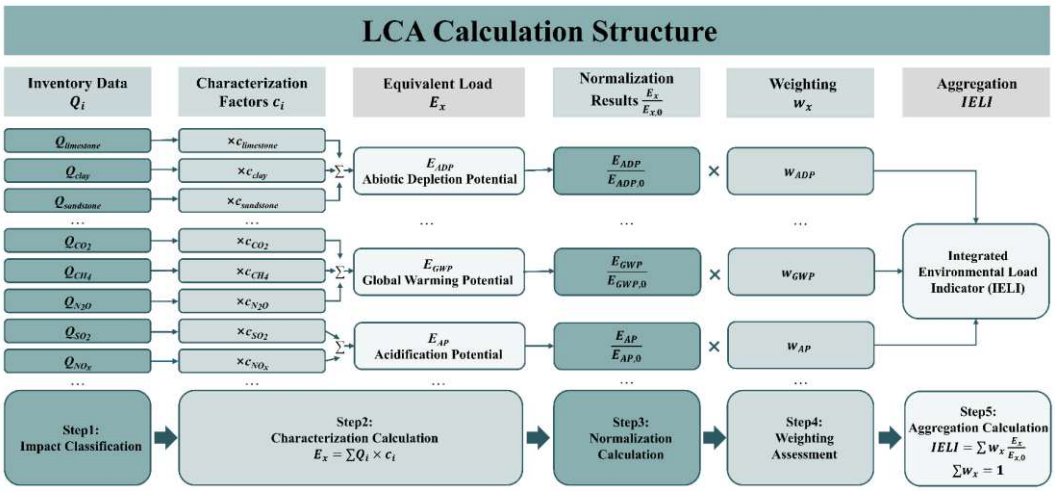


Fig. 6. Calculation structure of LCA.

Allocation of environmental burdens for inputs

This study adopted a multiple-case comparative design with a common reference scenario. All three lines employ new dry process cement production technology, with each representing a distinct technological pathway. To improve consistency across cases, all production lines were evaluated using a conventional P·O 42.5 cement reference and the same calculation method. Within this common framework, natural raw materials, industrial by-products, and co-processed wastes were treated separately according to the origins and technical functions of the alternative inputs used by each production line.

At the upstream stage, natural raw materials were first distinguished from industrial by-products. The environmental burdens of natural raw materials were calculated directly using actual LCI or background database data for extraction, processing, and transportation. For an industrial by-product generated jointly with a main product, the total environmental burden assigned to the by-product consisted of two components: the share of the upstream joint production burden allocated to the by-product and the burden arising from its subsequent treatment. The total burden was calculated as follows:

$$EL_{w,total} = m_w \times f_{w,up} + m_w \times f_{w,tr} \quad (3)$$

where $EL_{w,total}$ is the total environmental burden assigned to industrial by-product; m_w is the mass of industrial by-product; $f_{w,up}$ is the upstream joint production burden allocated per unit mass of the industrial by-product; and $f_{w,tr}$ is the environmental-burden factor associated with the subsequent treatment of the industrial by-product.

The upstream joint production burden allocated per unit mass of the industrial by-product was calculated using Eq. (4):

$$f_{w,up} = \frac{EL_{joint} \times C_a}{m_w}, C_a \in \{C_e, C_m\} \quad (4)$$

where EL_{joint} is the total environmental burden of the upstream joint production process that generates both the main product and the industrial by-product; C_a is the allocation coefficient applied in the calculation, corresponding to either the economic allocation coefficient C_e or the mass allocation coefficient C_m. Only one

of the two allocation methods was applied in an individual baseline calculation, and the results were not added together.

Under economic allocation, the share of the upstream burden assigned to the industrial by-product was determined from its share of the combined economic value of the main product and by-product. The economic allocation coefficient was calculated as follows:

$$C_e = \frac{m_w P_w}{m_w P_w + m_p P_p} \tag{5}$$

where C_e is the economic allocation coefficient; m_p is the mass of the main product generated jointly with the industrial by-product; and P_w and P_p are the unit economic values of the industrial by-product and main product, respectively. They must be expressed in the same monetary unit.

Under mass allocation, the share of the upstream burden assigned to the industrial by-product was determined from its share of the combined mass of the main product and by-product. The mass allocation coefficient was calculated as follows:

$$C_m = \frac{m_w}{m_w + m_p} \tag{6}$$

where C_m is the mass allocation coefficient. Where several industrial by-products were used in cement production, the environmental burden assigned to each by-product was calculated separately using Eq. (3)-(6), after which the individual results were summed.

Three representative cement production lines and their technological pathways

CUCC-NY produces cement using low-grade limestone and alternative raw materials and fuels. For this production line, solid wastes used as alternative raw materials and fuels were classified into resource-recovery and non-resource-recovery categories. And an appropriate allocation procedure was incorporated into the LCA framework to quantify reductions in IELI for different cement types produced using low-grade limestone and alternative raw materials and fuels. CUCC-XZ co-processes heavy metal-contaminated soil in its cement kiln. To account for the specific characteristics of this pathway, a dedicated “heavy metal accounting factor” was incorporated into the LCA framework. This factor was used to quantify reductions in

IELI for different cement types produced while co-processing heavy metal-contaminated soil. The IELI is calculated using Eq. (7), whereas Eq. (8) is used to calculate HTP while accounting for the impacts of heavy metals.

$$IELI = \sum w_x \frac{E_x}{E_{x,0}} = w_{ADP} \frac{E_{ADP}}{E_{ADP,0}} + w_{GWP} \frac{E_{GWP}}{E_{GWP,0}} + w_{HTP} \frac{E_{HTP}}{E_{HTP,0}} + \cdots w_{EP} \frac{E_{EP}}{E_{EP,0}} \quad (7)$$

$$\frac{\sum c_i \times Q_i}{E_{HTP,0}} \times w_{HTP} = \frac{c_{SO_2} \times Q_{SO_2} + \cdots - c_{hm} \times Q_{hm}}{E_{HTP,0}} \times w_{HTP} \quad (8)$$

where c_{hm} is the heavy metal characterization factor; Q_{hm} is the heavy metal content.

CRC-TY uses alternative raw materials and fuels in cement production and co-processes municipal solid waste as an alternative fuel in its cement kiln. Similarly, the solid wastes were classified into resource-recovery and non-resource-recovery categories, and an appropriate allocation procedure was applied to quantify the reductions in IELI for the different cement types produced using these alternative inputs. The case characteristics and distinctive technical functions of the three production lines are summarized in Table 3.

Table 3. Case attributes and featured technical functions of various production lines.

Production line name	Main alternative input/ co-processing object	Featured technical function
CUCC-NY	Low-grade limestone, Converter slag, Sulfuric acid residue, Fly ash, Textile waste, Carbon black	Use of low-grade limestone and alternative raw materials & fuels
CUCC-XZ	Furnace slag, Coal gangue, Heavy metal-contaminated soil	Cement kiln co-processing of heavy metal-contaminated soil
CRC-TY	Fly ash, Coal boiler slag, Municipal solid waste	Alternative raw materials & fuels and cement kiln co-processing of municipal solid waste

Based on the LCA methodology and the distinctive technical characteristics of the three production lines, the corresponding LCA calculation frameworks are illustrated in Fig. 7.

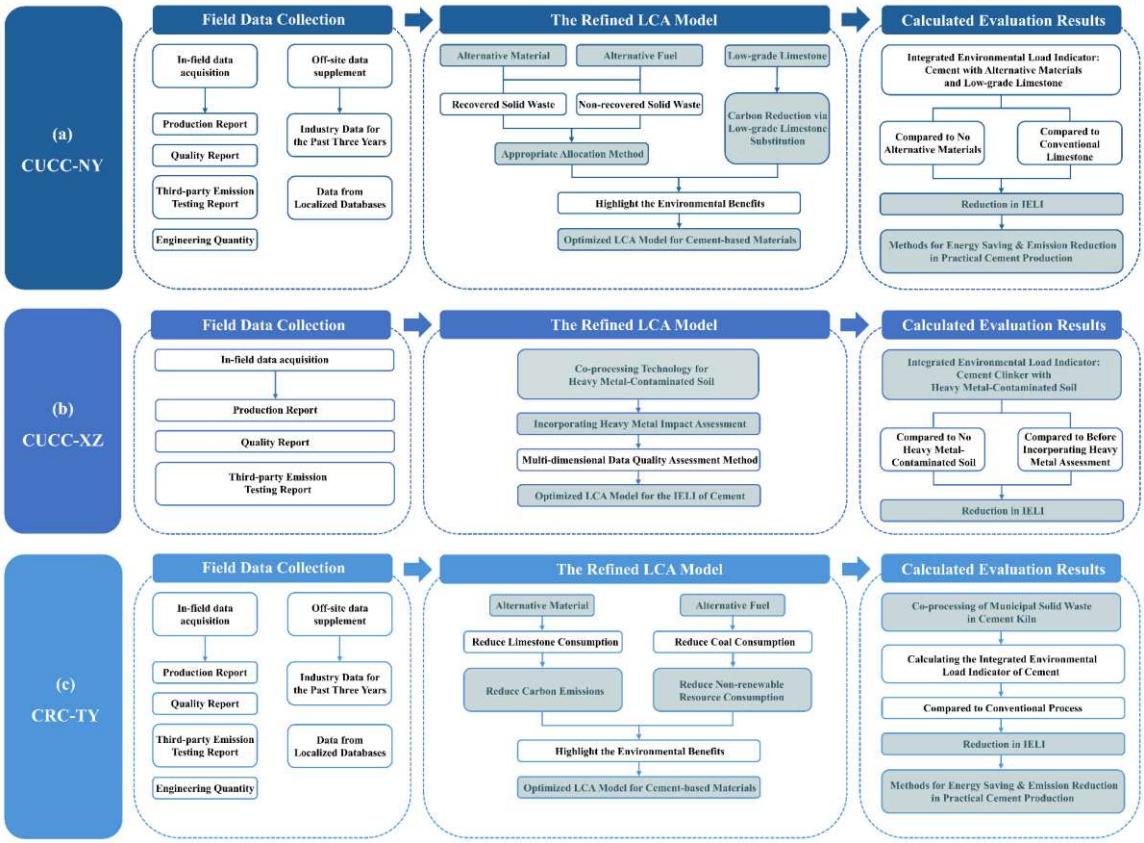


Fig. 7. Featured LCA accounting frameworks for three representative production lines.

(a)CUCC-NY; (b)CUCC-XZ; (c)CRC-TY.

Data availability

The production-line inventory data that can be publicly disclosed are provided in Table 1. The underlying plant-level operating records, online monitoring data, and third-party test reports contain commercially sensitive information and are subject to confidentiality agreements with the participating companies. The authors do not have permission to make these raw data publicly available.

Code availability

The LCA framework, calculation procedures, equations, and parameter settings used in this study are described in the Methods section. The codes used to process the life cycle inventory data and calculate the integrated environmental load indicator are available from the corresponding author on request.

References

1. USGS. Mineral commodity summaries 2026. *Mineral Commodity Summaries* (U.S. Geological Survey, Reston, 2026). https://doi.org/10.3133/mcs2026
2. Cheng, D. et al. Projecting future carbon emissions from cement production in developing countries. *Nat. Commun.* **14**, 8213 (2023).
3. Shah, I. H., Miller, S. A., Jiang, D. & Myers, R. J. Cement substitution with secondary materials can reduce annual global CO_2 emissions by up to 1.3 gigatons. *Nat. Commun.* **13**, 5758 (2022).
4. Georgiades, M., Shah, I. H., Steubing, B., Cheeseman, C. & Myers, R. J. Prospective life cycle assessment of European cement production. *Resour. Conserv. Recycl.* **194**, 106998 (2023).
5. Liu, Y. et al. Life cycle assessment of beneficial use of calcium carbide sludge in cement clinker production: A case study in China. *J. Clean. Prod.* **418**, 138003 (2023).
6. Clark, G., Davis, M., Shibani & Kumar, A. Assessment of fuel switching as a decarbonization strategy in the cement sector. *Energy Convers. Manag.* **312**, 118585 (2024).
7. Jacob, R. M. & Tokheim, L.-A. Electrified calciner concept for CO_2 capture in pyro-processing of a dry process cement plant. *Energy* **268**, 126673 (2023).
8. Quevedo Parra, S. & Romano, M. C. Decarbonization of cement production by electrification. *J. Clean. Prod.* **425**, 138913 (2023).
9. Antzaras, A. N., Papalas, T., Heracleous, E. & Kouris, C. Techno-economic and environmental assessment of CO_2 capture technologies in the cement industry. *J. Clean. Prod.* **428**, 139330 (2023).
10. Løge, I. A. et al. Pilot-scale CO_2 capture in a cement plant with CESAR1: Leveraging absorber intercooling and cold-feed heat-integration to lower the SRD. *Chem. Eng. J.* **524**, 169153 (2025).
11. Zhang, C., Yu, B., Chen, J. & Wei, Y. Green transition pathways for cement industry in China. *Resour. Conserv. Recycl.* **166**, 105355 (2021).
12. Qu, J. et al. Plant-level emissions and synergistic control of pollutants and carbon dioxide in China's cement industry based on real-time monitoring data. *Earth's Future* **13**, e2025EF006035 (2025).
13. ISO. ISO 14040: Environmental management — Life cycle assessment — Principles and framework (International Organization for Standardization, Geneva, 2006).
14. Guo, J. et al. Shedding light on the shadows: Transparency challenge in background life cycle inventory data. *J. Ind. Ecol.* **29**, 766-776 (2025).
15. Rihner, M. C. S. et al. Life cycle assessment in energy-intensive industries: Cement, steel, glass, plastic. *Renew. Sustain. Energy Rev.* **211**, 115245 (2025).
16. Tang, L. et al. Plant-level real-time monitoring data reveal substantial abatement potential of air pollution and CO_2 in China’s cement sector. *One Earth* **5**, 892-906 (2022).
17. Wang, W., Ye, M., Shi, Y. & Xiao, D. Plant-level intensity of energy and CO_2

emissions for Portland cement in Guizhou of Southwest China 2019-2022. *Sci. Data* **11**, 759 (2024).
18. Zhang, J., Cui, K., Yang, Y. & Chang, J. Investigation on the preparation of low carbon cement materials from industrial solid waste phosphogypsum: Clinker preparation, cement properties, and hydration mechanism. *J. Clean. Prod.* **452**, 142203 (2024).
19. Liu, W. et al. Hazardous waste alternative fuels to novel ecological energy: Combustion characteristics and effects on clinker's environmental safety. *Ceram. Int.* **50**, 48736-48754 (2024).
20. Liu, C. et al. Volatilization characteristic and solidification of Pb, Zn, Cd and As during cement kiln co-processing of solid waste. *Constr. Build. Mater.* **406**, 133410 (2023).
21. Sharma, P., Sheth, P. N. & Sen, S. Aspen plus simulation of an inline calciner for white cement production with a fuel mix of petcoke and producer gas. *Energy* **282**, 128892 (2023).
22. Terán-Cuadrado, G., Nurdiawati, A. & Al-Ghamdi, S. G. Comparative prospective life cycle assessment of decarbonization strategies in the Saudi cement industry. *Environ. Impact Assess. Rev.* **119**, 108362 (2026).
23. Løge, I. A. et al. Pilot-scale CO_2 capture in a cement plant with CESAR1: Comparative analysis of specific reboiler duty across advanced process configurations. *Chem. Eng. J.* **506**, 159429 (2025).
24. Ostroski, A., Rapp, V. H. & Scown, C. D. Air emissions impacts of fuel substitution in the United States cement industry. *Environ. Sci. Technol.* **60**, 20874-20887 (2026).
25. Xu, X. et al. Modernizing cement manufacturing in China leads to substantial environmental gains. *Commun. Earth Environ.* **3**, 276 (2022).
26. Coffetti, D. et al. Pathways towards sustainable concrete. *Cem. Concr. Res.* **154**, 106718 (2022).
27. Rhaouti, Y., Taha, Y. & Benzaazoua, M. Assessment of the environmental performance of blended cements from a life cycle perspective: A systematic review. *Sustain. Prod. Consum.* **36**, 32-48 (2023).
28. Chang, J., Cho, Y. & Lin, Y. Regeneration of heavy metal contaminated soils for cement production by cement kiln co-processing. *Resour. Conserv. Recycl.* **176**, 105909 (2022).
29. Kusuma, R. T., Hiremath, R. B., Rajesh, P., Kumar, B. & Renukappa, S. Sustainable transition towards biomass-based cement industry: A review. *Renew. Sustain. Energy Rev.* **163**, 112503 (2022).
30. Santos-Montes, A. M., González-Arechavala, Y., Martin-Sastre, C., Lefranc, L. & Linares, J. I. Life cycle assessment of clinker and cement production in Spain. Environmental assessment of decarbonisation measures. *Clean. Environ. Syst.* **18**, 100290 (2025).
31. Dahanni, H. et al. Life cycle assessment of cement: Are existing data and models relevant to assess the cement industry's climate change mitigation strategies? A literature review. *Constr. Build. Mater.* **411**, 134415 (2024).

32. Olsson, J. A., Miller, S. A. & Kneifel, J. D. A review of current practice for life cycle assessment of cement and concrete. *Resour. Conserv. Recycl.* **206**, 107619 (2024).
33. Navia, R., Rivela, B., Lorber, K. E. & Méndez, R. Recycling contaminated soil as alternative raw material in cement facilities: Life cycle assessment. *Resour. Conserv. Recycl.* **48**, 339-356 (2006).
34. Fozer, D., Owsianiak, M. & Hauschild, M. Z. Prospective life cycle assessment of solid recovered fuel utilization and marine fuel production in cement plants. *Sustain. Prod. Consum.* **55**, 117-131 (2025).
35. Kosajan, V. et al. Comprehensive assessment of cement kiln co-processing under MSW sustainable management requirements. *Resour. Conserv. Recycl.* **174**, 105816 (2021).
36. Thwe, E., Khatiwada, D. & Gasparatos, A. Life cycle assessment of a cement plant in Naypyitaw, Myanmar. *Clean. Environ. Syst.* **2**, 100007 (2021).
37. Wolde, M. G., Khatiwada, D., Bekele, G. & Palm, B. A life cycle assessment of clinker and cement production in Ethiopia. *Clean. Environ. Syst.* **13**, 100180 (2024).
38. Olsson, J. A., Miller, S. A. & Alexander, M. G. Near-term pathways for decarbonizing global concrete production. *Nat. Commun.* **14**, 4574 (2023).
39. Supriya, Chaudhury, R., Sharma, U., Thapliyal, P. C. & Singh, L. P. Low-CO_2 emission strategies to achieve net zero target in cement sector. *J. Clean. Prod.* **417**, 137466 (2023).
40. ISO. ISO 14044: Environmental management — Life cycle assessment — Requirements and guidelines (International Organization for Standardization, Geneva, 2006).
41. Dang, W. et al. Decarbonization and clean production in China's cement industry: Strategies from the LEAP-LCA perspective. *Environ. Impact Assess. Rev.* **116**, 108124 (2026).
42. NRA. 2021 Railway Statistical Bulletin. https://www.mot.gov.cn/shuju/tongjishuju/tielu/202601/P020260104367334874298.pdf (2022).
43. NRA. 2023 Railway Statistical Bulletin. https://www.mot.gov.cn/shuju/fenxigongbao/hangyegongbao/202601/P020260127538858021035.pdf (2024).
44. Ismaeel, W. S. E. Midpoint and endpoint impact categories in green building rating systems. *J. Clean. Prod.* **182**, 783-793 (2018).
45. Li, Y., Liu, Z., Ren, B., Tao, C. & Guo, X. Coupling evaluation of environmental load and mechanical properties for co-processing of MSW in cement kiln. *J. Build. Mater.* **27**, 299-308 (2024) (in Chinese).
46. Guo, X. et al. Carbon reduction in cement industry - An indigenized questionnaire on environmental impacts and key parameters of life cycle assessment (LCA) in China. *J. Clean. Prod.* **426**, 139022 (2023).

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Authorship contributions

Z.H., Y.R. and X.G. conceived the study. Z.H. and Y.R. developed the methodology. C.Q. and X.G. supervised the research. Z.H., L.M., H.L., W.L., C.T., Y.G., Q.S., A.S. and Y.R. conducted the investigation. C.Q., L.M., H.L., W.L., C.T., Y.G., Q.S. and A.S. contributed to the validation of the data and results. Z.H., C.T., Y.G. and Y.R. prepared the figures and visualizations. Z.H. drafted the manuscript, and X.G. reviewed and edited it. C.Q. and X.G. acquired funding. All authors discussed the results and reviewed and approved the final manuscript.

Competing interests

The authors declare no competing interests.