Proceedings of the 2nd International Conference on Functional Materials and Civil Engineering
DOI: 10.54254/2755-2721/72/20241009

Research on the life cycle assessment of cement

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Abstract. Man-made carbon emissions from the cement sector rank second only to steel, comprising 5% of the total emissions. Additionally, the cement industry accounts for 12–15% of annual energy consumption in the global industrial sector. Given the escalating climate and energy challenges, there's a growing focus on environmental impact assessments and research into low-carbon cement. Engineers are increasingly striving for carbon neutrality in cement production. Life cycle assessment (LCA) emerges as a vital tool for analyzing the environmental impact of materials throughout their lifecycle. Current research assesses LCA's applicability in the cement industry, evaluating mitigation strategies and common models. Efforts towards reducing environmental impact and optimizing cement performance are reviewed, though limitations of the LCA model in this context are noted.

Keywords: life cycle assessment (LCA), cement, carbon emissions, carbon neutral, Integrated environmental load

1. Introduction

As urbanization accelerates globally, the demand for cement steadily rises. Projections indicate that by 2050, global cement production could soar to 468.2 million tons annually, driven predominantly by developing countries [1,2]. Cement manufacturing, a multifaceted process, demands substantial resources, including raw materials like limestone and clay, alongside significant energy inputs such as fossil fuels, heat, and electricity. This energy-intensive industry contributes significantly to carbon emissions, accounting for 5% of the total, and consumes 12–15% of the world's industrial energy [3]. These emissions include harmful gases like SO2 and NO2, which pose significant environmental risks. The Ministry of Environmental Protection of China has highlighted the irreversible harm such emissions can inflict on the environment [4]. To comprehensively assess the environmental impact, a holistic approach is necessary [5], integrating various factors such as resource consumption and waste discharge. This is where life cycle assessment (LCA) proves invaluable, providing a methodological framework to evaluate the integrated environmental load of cement production. This paper utilizes LCA methodology to systematically assess the environmental impact of cement production, discussing the intricacies of the evaluation process and proposing strategies for industry improvement and sustainability.

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2. Life cycle assessment of cement

According to the ISO 14040 standard [6], life cycle assessment consists of four key steps: objective and scope determination, life cycle inventory analysis (LCI), life cycle impact assessment (LAC), and life cycle interpretation. However, in the actual use of LCA evaluation of cement, the method is different because of the actual production technology, raw materials of cement [7,8].

2.1. Goal and scope definition

Goal and scope determination in life cycle assessment (LCA) involves establishing the functional unit and system boundary of the research object, providing the foundation for subsequent analysis [6]. In cement LCA, the system boundary typically adopts a "cradle to gate" approach, covering assessment from resource extraction to the factory gate. Some studies extend this scope to "cradle to grave," considering the product's use and disposal stages. Alternatively, concepts like "cradle to cradle" and "door to door" are also explored, especially given cement's diverse applications in the final use stage, making it challenging to capture every step [9-11]. The system boundaries typically encompass energy, fuels, and the extraction, transportation, and emissions of raw materials. Figure 1 shows the common system boundaries of cement production. However, some studies omit data on the extraction and transportation of cement raw materials due to information challenges [11-13].

Functional units serve as the basis for normalizing the input and output data of the system [14]. The selection of functional units must be carefully defined based on the study's purpose, time span, and geographical breadth, as this can significantly impact the results. For instance, different studies use varied functional units such as a ton of cement, a ton of Portland cement with specific strength, or one ton of clinker, leading to notably different comparison results [12,15,16].

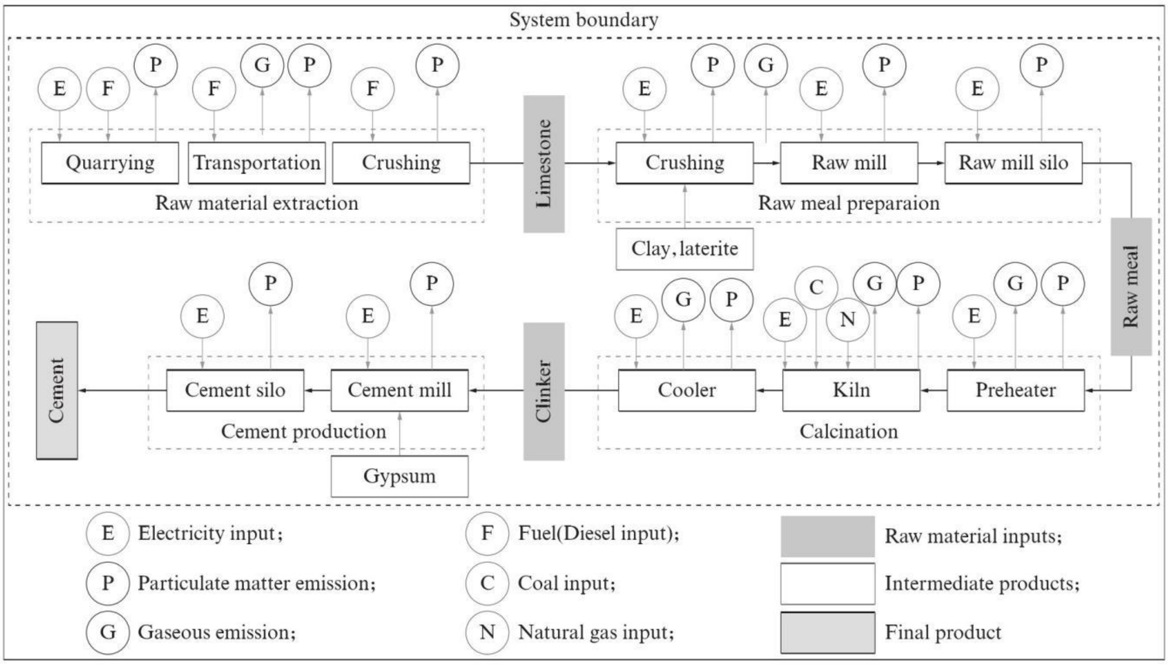

Figure 1. Common system boundaries of cement production [17]

2.2. Life cycle inventory analysis (LCI)

Life cycle inventory analysis involves gathering and summarizing input and output data across the entire life cycle of cement [7]. Input data includes energy and material consumption, as well as water usage during manufacturing. Transportation details, including type and distance, are also considered, though some studies may overlook raw material transportation due to data challenges [18]. Output data encompasses emissions of gaseous, solid, and liquid waste throughout the life cycle. ISO

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standards outline three methods for assessing data quality: completeness, consistency, and sensitivity checks [10]. Given regional variations in raw materials, fuels, and electricity, constructing local datasets is essential to avoid misinterpretation of global datasets. Practitioners should exercise caution to prevent erroneous conclusions arising from dataset misuse [19].

2.2.1. Input data inventory. Cement production relies on raw materials such as limestone, clay, gypsum, and iron powder. On average, 1 ton of clinker production requires 1.5 to 1.7 tons of raw materials [16], with regional variations, for instance, in China, it ranges from 1.5 to 1.9 tons [13]. Input resource statistics depend on the system boundary considered, with "cradle" studies starting from mining and "grave" studies ending with resource recovery and waste disposal. However, the most significant energy consumption and resource input occur at the "gate" stage, primarily heat and electricity. Processing electricity data poses challenges due to variations in electricity production methods across countries [20]. Thermal energy for cement production, mainly from coal, petroleum coke, and alternative fuels, is also significant [21]. Research explores the feasibility of alternative fuels [13], with studies indicating that 1 ton of clinker requires around 0.128 tons of standard coal. Additionally, processes like crushing, grinding, and cooling consume approximately 21.37 kWh per ton. Freshwater resource input in cement production is minimal, around 0.165 cubic meters per ton, with a high recovery rate, hence often overlooked in studies [13,22].

2.2.2. Output data inventory. Cement production primarily emits atmospheric pollutants, notably CO2, SO2, NOx, particulate matter (PM), as well as HCl, fluoride, VOCs, and noise, with minimal solid waste except for dust from cement kilns [23]. Emissions primarily occur during the calcination stage. Studies analyzing cement's impact on human health, ecology, and resources through LCA highlight human health as the most affected category, mainly due to respiratory effects [24]. Carbon emissions in the cement industry are categorized into direct and indirect emissions. Direct emissions stem from feedstock decomposition and fossil fuel combustion, accounting for clinker coefficient and combustion efficiency. Nitrogen emissions result from fuel oxidation and thermal fixation during combustion, leading to NOx formation. Sulfur dioxide emissions are contingent on fuel sulfur content, with 1 ton of clinker production emitting 0.048-0.150 kg of SO2 and 0.900-2.200 kg of NOx [13]. Other pollutant emissions, such as VOCs, are measured as total organic compounds (TOC). Solid waste and sewage are typically excluded from cement LCA studies due to their minimal output.

2.2.3. Alternative feedstock and alternative fuel considerations. As global sustainability becomes increasingly paramount, research on low-carbon cement emphasizes finding alternative fuels and raw materials. However, challenges persist. For instance, while increased use of alternative fuels reduces total carbon emissions, it also leads to heightened production of heavy metals [25]. Current research focuses on utilizing combustible waste like garbage and biomass, as well as renewable energy sources such as green hydrogen and photovoltaic, to reduce reliance on traditional fossil fuels like coal [13]. Regarding alternative raw materials, calcium-rich industrial waste like calcium carbide slag and steel slag can substitute for limestone, conserving natural mineral resources. However, the availability of calcium-rich waste often falls short of meeting cement production demands [25,26].

2.3. Life cycle impact assessment (LCIA)

Life cycle impact assessment is a qualitative description and quantitative assessment of the size and importance of the environmental load in the whole life cycle of the product according to the input and output data in the inventory analysis [6].

2.3.1. *Definition and selection of environmental load distribution mode.* In assessing the environmental impact of the cement industry's process from raw material extraction (cradle) to waste disposal (grave), LCA models employ various allocation methods to determine the main products, by-products, and secondary products [19]. These methods include no distribution, distribution based on

DOI: 10.54254/2755-2721/72/20241009

quality (highest environmental load), and distribution according to economic value. However, there's no unified approach regarding whether to consider the environmental burden of upstream production and use when evaluating alternative raw materials and fuels. Proportional allocation is a common method, although the allocation ratio remains variable [27,28].

2.3.2. Impact classification. Impact classification in Life Cycle Impact Assessment (LCIA) involves qualitatively analyzing the environmental load of each item in the life cycle and establishing its relationship with environmental impact types. LCIA models include endpoint models (e.g., EPS2000), midpoint models (CML2001), and hybrid models (IMPACT2002+). The choice of model type depends on whether it's problem-oriented or damage-oriented; for instance, the midpoint model is suitable for analyzing cement production [29,30]. Figure 2 illustrates Guo's study, which used the IMPACT2002+ model to outline the basic framework of LCIA impact classification in cement production, with a focus on four damage types: human health, ecological quality, resource consumption, and climate change [30].

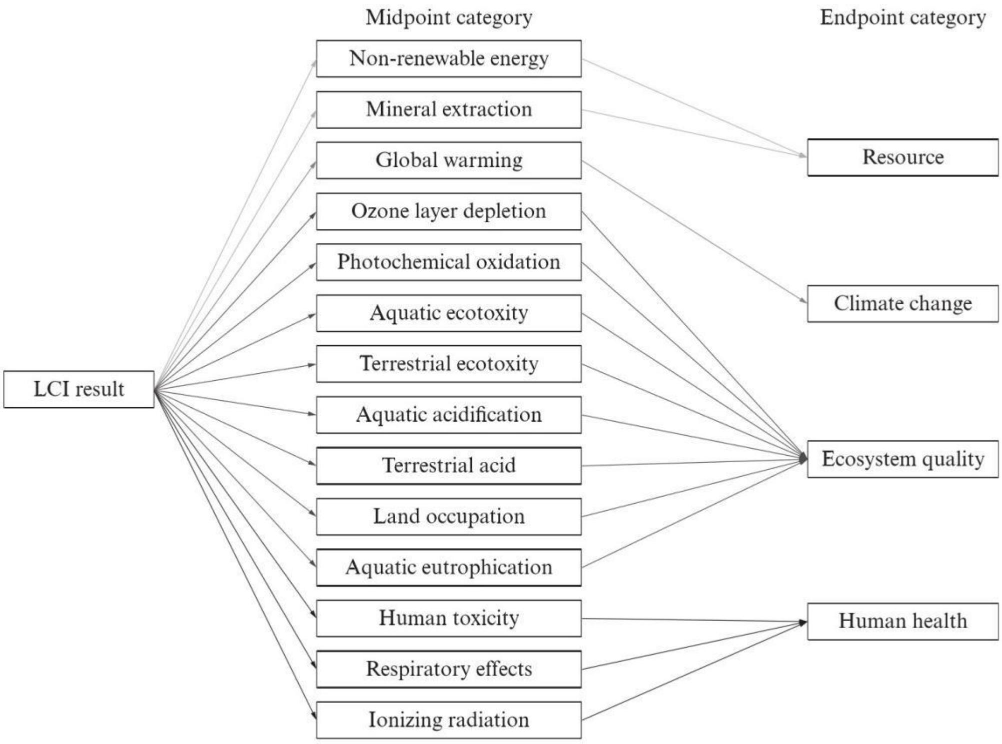

Figure 2. Overall framework of IMPACT2002+model [31]

Research in this field has diversified, with studies examining various aspects. Boesch et al. conducted LCIA on different cement types, focusing on climate change, human toxicity, acidification, and eutrophication [12]. Other studies have concentrated on specific stages of cement production, such as calcination and clinker formation [16]. However, the challenge arises when environmental load boundaries encompass multiple categories, like CH4, NOx, and SO2 emissions. In such cases, distribution coefficients are utilized to allocate these loads into distinct environmental impact categories, employing parallel or series mechanisms [30].

2.3.3. *Characterization.* Impact classification serves as a qualitative analysis, but quantification is necessary. Characteristic factors (C_i) are introduced to quantify the impact intensity of inventory items (Q_i) on corresponding environmental categories, summarizing the environmental equivalent value (E_x). However, there's no standard for selecting characteristic equivalents for non-renewable resource consumption (ADP), leading to challenges in comparing research results. Additionally, the scope of environmental impact category selection (local, regional, global) must be considered, as effects across different ranges cannot be directly compared. Moreover, some environmental impact categories may require regional modifications to account for regional characteristics, as demonstrated by Liu's localized adjustments to land occupation calculations [31].

2.3.4. Normalization. To facilitate comparison, the environmental equivalent values (E_x) derived from characteristic factors need normalization. Ex is assigned as the base value ($E_{x,0}$) and treated as dimensionless. The ratio of E_x to $E_{x,0}$ is calculated. Typically, total emissions or total resource and energy consumption within a specific range serve as the baseline value worldwide [32]. However, normalized values cannot be directly compared. To compare the integrated environmental loads of different systems, normalized results of each impact category must be assessed, with corresponding weight coefficients (ω_x) assigned based on relative importance. Weighted calculation yields the integrated environmental load value.

3. Limitation of cement LCA

LCA, while widely used for assessing cement production's environmental impact, faces standardization challenges in defining system boundaries, resulting in subjective selections and diverse outcomes. Moreover, unclear data selection rules contribute to discrepancies in including factors like heavy metal emissions and freshwater resource input. Furthermore, existing studies lack adequate evaluation and discussion of data quality, particularly scene data, which is difficult to verify. Future research should prioritize data verification in cement LCA studies and integrate environmental impact assessment with performance, cost, and economic benefits for a more comprehensive analysis.

4. Conclusion

Cement LCA primarily focuses on energy consumption and greenhouse gas emissions during production, with a "cradle to gate" boundary. However, expanding the boundary to cover the entire lifecycle, from raw material extraction to application and recovery, is essential to meet the "dual carbon" goal and utilize solid waste resources effectively. Establishing standardized LCA rules for comprehensive environmental load evaluation, ensuring data transparency, and addressing boundary limitations are critical for future research. Integrating environmental load evaluation with performance metrics can optimize cement performance while reducing environmental impact, promoting comprehensive benefit evaluation.

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