Clean Technologies and Environmental Policy (2024) 26:579–597
https://doi.org/10.1007/s10098-023-02683-0

REVIEW

Carbon emissions mitigation methods for cement industry using a systems dynamics model

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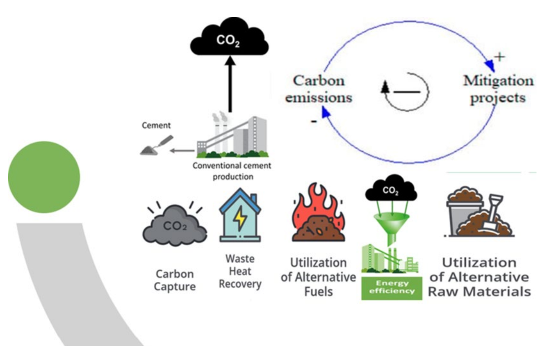
Received: 23 August 2023 / Accepted: 14 November 2023 / Published online: 9 January 2024

Abstract

Cement production contributes significantly to anthropogenic greenhouse gas emissions (GHG), a major contributor to global carbon emissions. The environmental impacts of cement production have grown in recent years and it is urgent to reduce its carbon footprint. Systems dynamics (SD) is a simulation method used to understand the nonlinear behavior of complex systems over time. It is commonly used in various sectors to predict emissions and conduct policy experiments. Due to the poor implementation of carbon mitigation strategies within the cement industry, enhancing policymaking by employing more advanced decision-support tools is necessary. This paper reviews previous studies that use the SD approach to assess and compare different mitigation strategies proposed and implemented to reduce carbon emissions in the cement industry. These strategies encompass technological advancements and process improvements, including using alternative fuels and raw materials (adopting low-carbon cementitious materials), energy efficiency improvements, carbon capture and storage and waste heat recovery. The review examines the papers' scope, model descriptions, validation method and mitigation methods highlighted in each study, providing valuable insights for decision makers in the cement industry. Furthermore, the paper discusses the limitations and gaps related to SD modeling, highlighting important factors such as stakeholder engagement in designing effective carbon mitigation strategies. The reviewed studies constantly emphasized technical strategies for mitigating carbon emissions from the cement industry, as stated by the International Energy Agency (IEA) classification. Innovative and emerging technologies, such as WHR, depends on adequate funding, motivation and research and development. However, they frequently neglected to address the barriers hindering their implementation or provide detailed policy measures to overcome them using SD. Additional research is required to assess the practicality and costs of implementing these strategies.

Graphical abstract

Navigating the way to sustainability in the cement industry: Exploring mitigation strategies through systems dynamics model



Keywords Systems dynamics · GHG mitigation · Mitigation policy · Mitigation options · Cement industry

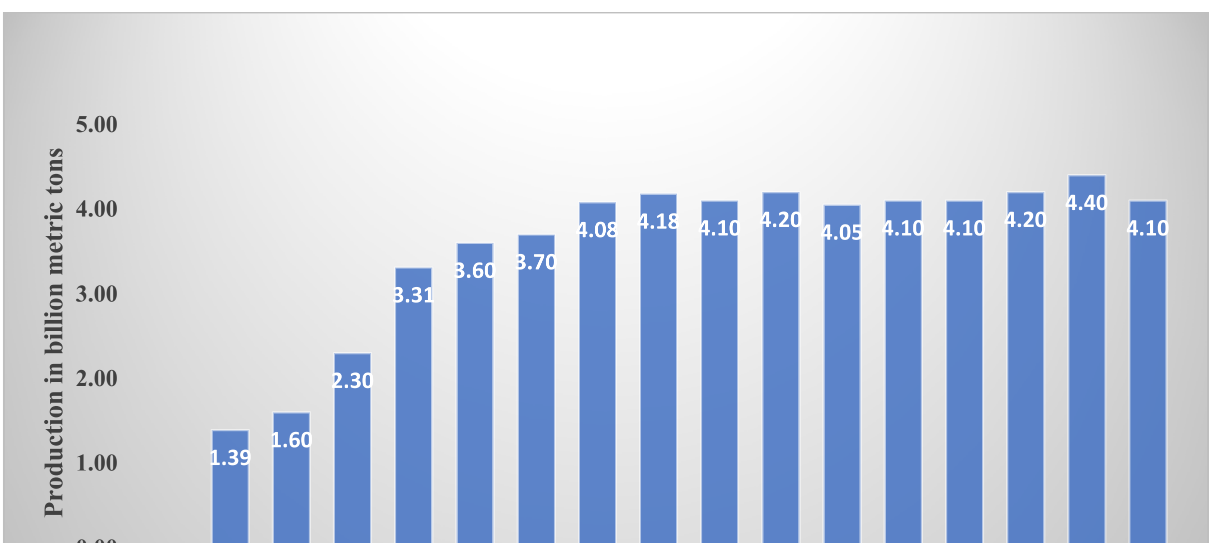
Extended author information available on the last page of the article

Introduction

Climate change has been identified as a leading cause of the threat to the planet today due to human activity, as evidenced (IPCC 2018). The impact of human actions alone has resulted in a rise of 1 °C in average global temperatures compared to the period before the Industrial Revolution. Projections indicate that by 2046, the average global temperature will rise by 1.5 °C, as forecast at the beginning of this century (Tang et al. 2022). Cement is a widely used construction material and its production has increased since the middle of the nineteenth century. In 2022, global cement production was approximately 4.2 billion tons, a significant increase compared to 1.39 billion tons in 1995 and produced by more than 90% of countries and territories (Cembureau 2021), surpassing the 3.69–4.40 billion tons projected production by the International Energy Agency (IEA) by 2050 (IEA 2009). This growth in cement production serves as evidence of the substantial expansion of the construction industry over the years. Global cement production reached 4.1 billion metric tonnes in 2022 as shown in Figure1.

According to the United States Geological Survey (USGS) (2021) and the European Cement Association Cembureau (2021), China was the largest producer of cement, with 57.2% of the total production globally, followed by India (7.0%), the European Union (6.1%), the USA (2.1%) and the others 27.6%. As shown in Fig. 2, China led global cement production, producing an enormous 2.1 billion Mt. in 2022, which surpasses any other country by a significant margin. China produced more than 50% of total global cement production in 2022. India, the second-largest cement producer worldwide, fell far behind with a production volume of 370 million Mt. Vietnam was third on the worldwide list, producing 120 million Mt. of cement the same year. In 2022, the USA produced approximately 95 Mt. of cement and came fourth among the top cement-producing countries worldwide. Cement production consumes a substantial amount of energy and produces a significant amount of carbon dioxide (CO_2). Portland cement, the most widely used type of cement globally, is produced by grinding Portland cement clinker, a hydraulic substance primarily consisting of calcium silicates (Wang et al. 2014).

The cement production process emits approximately 0.9 tons of CO_2 per ton of cement (Hasanbeigi et al. 2010), accounting for about 5–8% of global CO_2 emissions and ranking as the second-largest CO_2 emissions source (Mikulčić et al. 2016; Kajaste and Hurme 2016). According to the Intergovernmental Panel on Climate Change (IPCC) report, the cement industry was responsible for 7% of global anthropogenic CO_2 emissions in 2005 (Bert et al. 2005). In 2019, the cement industry generated 2.4 gigatonnes (Gt) of CO_2, constituting 26% of the overall emissions from the industrial sector (IEA 2020). In cement production, almost 50% of GHG emissions are from material consumption, while approximately 40% originates from fuel combustion. The remaining 10% is divided equally between electricity usage and transportation (Maddalena et al. 2018;



	1995	2000	2005	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022*
■	1.39	1.60	2.30	3.31	3.60	3.70	4.08	4.18	4.10	4.20	4.05	4.10	4.10	4.20	4.40	4.10

Fig. 1 Cement production worldwide from 1995 to 2022 (Billion metric tons) (Garside 2022b)

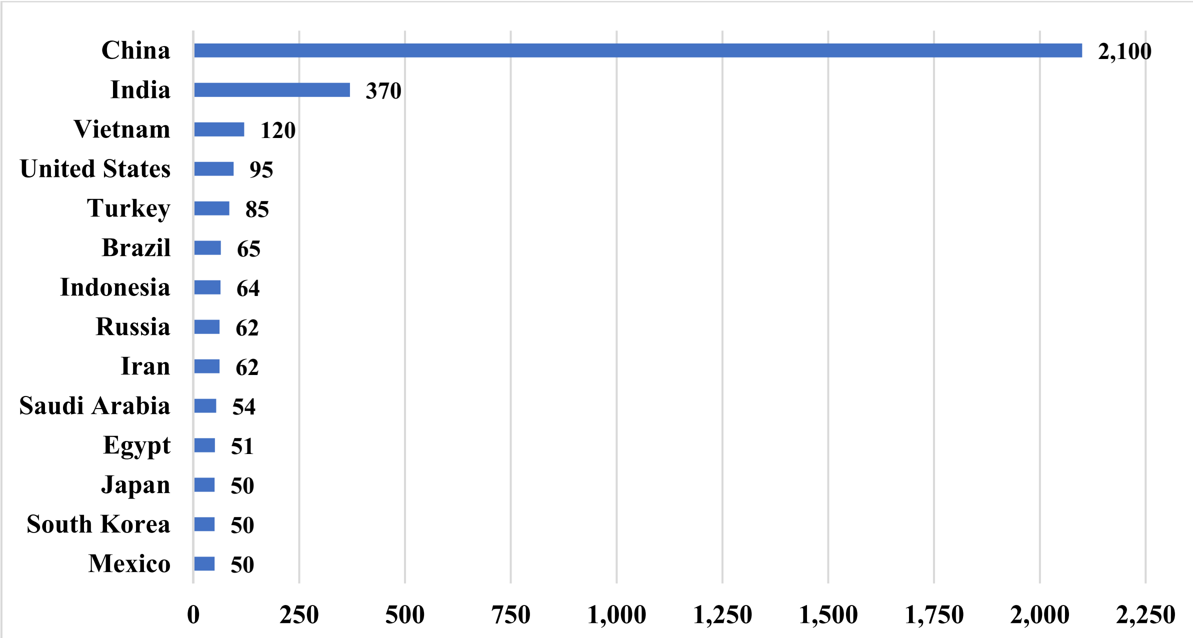


Fig. 2 Major countries in worldwide cement production in 2022 (Garside 2022c)

Summerbell et al. 2016). In 2021, global emission cement production raised to about 1.7 billion metric tons of carbon dioxide (CO_2) into the atmosphere. These emissions have experienced a significant rise since the 1960s and have more than doubled since the beginning of the twenty-first century, as shown in Fig. 3. The annual global production of cement exceeds four billion metric tons.

As cement production continues to increase, CO_2 emissions also increase. Burning of various substances such as coal, natural gas, heavy fuel oil, biomass, petro-coke, waste fuel or fuel oil generates energy. Coal is the primary and traditional energy source in South Africa, China and other countries (Pereira et al. 2011). Clinker production, the main component of Portland cement, emits approximately 0.527 tonnes of CO_2/ton clinker, specifically from the calcination process representing 50% of the emissions within the cement production process (He 2009). The rest of the emissions are released from carbon fuels and electricity usage (Worrell et al. 2001). These stages consume different amounts of energy, with clinker burning being responsible for the highest percentage of energy consumption (25%), followed by finish grinding (40%),

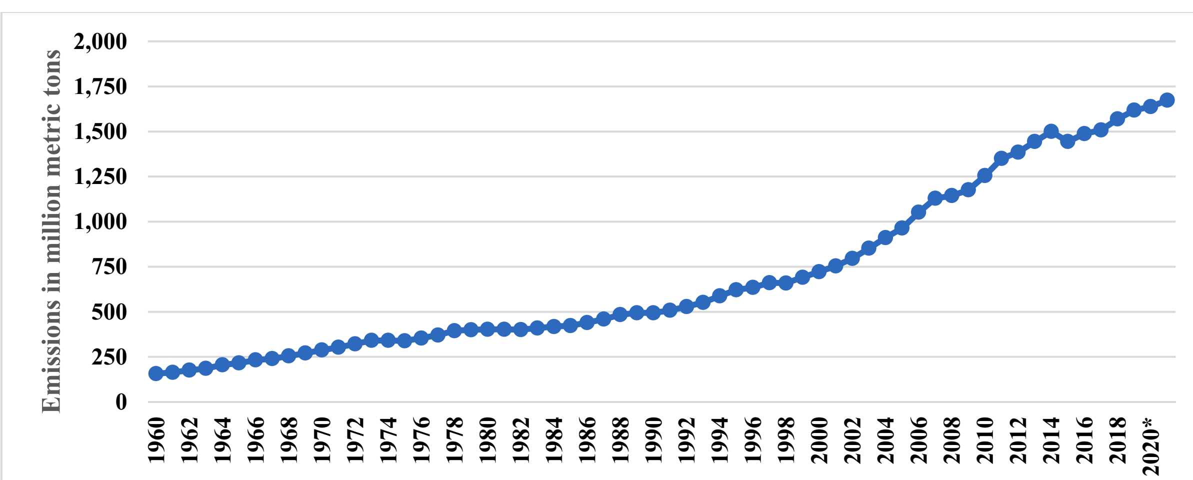


Fig. 3 Carbon dioxide emissions from the manufacture of cement worldwide from 1960 to 2021 (Garside 2022a)

raw grinding (20%) and auxiliary grinding (15%) (Madlool et al. 2011).

Decarbonizing this sector is crucial to address climate change. Consequently, extensive research and analysis have been conducted on practical solutions for decarbonization, as demonstrated by these studies (Fennell et al. 2021; Habert et al. 2020; Pamenter and Myers 2021). Due to the substantial GHG emissions emitted by the cement industry and its contribution to climate change, the industry has become a key focus for reducing emissions in international accords. These agreements, including the Paris Agreement under the United Nations Framework Convention on Climate Change, aim to limit global warming below 2 °C or possibly close to 1.5 (Rockström et al. 2017; Fonta 2017). The Low Carbon Technology Partnerships Initiative (LCTPi), a program led by the World Business Council for Sustainable Development (WBCSD), has developed the Cement Action Plan. This plan aims to reduce emissions by 20–25% by 2030 and involves collaboration with major cement producers in over 100 countries, representing 30% of global production (Change 2017). Therefore, adopting low-carbon technologies in the cement industry is crucial to promote sustainable development.

The system dynamics (SD) method analyzes complex and extensive systems. Unlike focusing solely on a single transaction, the SD method investigates the relationships between modeling and various variables within a system (Koelling and Schwandt 2005; Tigress et al. 2000). In the mid-twentieth century, Forrester developed the SD model based on feedback control theory to explain the dynamic behavior of systems (Brown and Campbell 1948; Macmillan 2016; Schaefer 1950; Forrester 1961). This method has gained significant attention for its effectiveness in predicting interconnected variables since proposed by Jay W. Forrester (Feng et al. 2013). The main aim of an SD is to comprehend and explain the nonlinear behavior of crucial factors and their interactions with each other and to examine the relationship between policies, decision-making processes, system structure and time delays, which affect the development and stability of a specific system (Dong et al. 2012). To achieve this, SD models utilize positive (+) and negative (−) sign feedback loops to illustrate the dynamics generated by these interactions. Various simulation methods, such as multi-agent-based simulation (Zhou et al. 2016; Wu et al. 2017), Monte Carlo (Liu et al. 2020; Zhu et al. 2018), discrete event simulation (Li and Akhavian 2017) and SD (Procter et al. 2017; Barisa and Rosa 2018; Ekinci et al. 2020), are commonly used to assess mitigation policies and their resulting carbon emissions depending on desired goals. It is a comprehensive simulation method and is becoming increasingly popular in carbon policy evaluation due to its capacity to deal with complex socioeconomic factors and forecasting trends like cement demand (Tang et al. 2020; Ekinci et al. 2020).

The share of CO_2 emissions during cement production is illustrated in Fig. 4, indicating their sources. Nearly half of the CO_2 emissions are generated during calcination, making them inevitable when producing Portland cement clinker. The cement industry is distinguished from other industries that emit GHG emissions primarily due to fuel combustion. Approximately 40% of GHG emissions in cement production come from fuel combustion to generate the heat required for the calcining process. According to the IEA calculations in 2018 (IEA 2018), 40% of emissions were associated with fuel combustion, 22% were directly attributed to the energy used for calcination, and 18% were caused by heat loss. Approximately 5% of total emissions come from electricity for cooling and grinding, while another 5% are attributed to transportation for cement distribution and storage.

As a result, the sector is naturally a significant contributor to CO_2 emissions since the process produces emissions by the primary chemical reaction of converting limestone

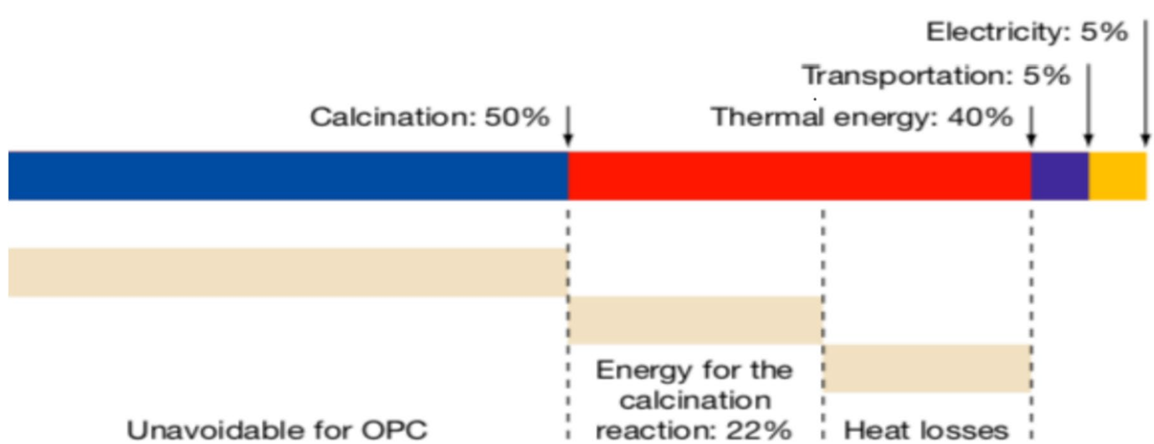


Fig. 4 The share of CO_2 emissions during cement production (Lowitt 2020)

($CaCO_3$) to lime (CaO). In an average cement plant, the production of one ton of cement results in the emission of approximately 0.5–0.9 tons of CO_2 (Rubenstein 2012). The exact amount of emission varies depending on the production process, heat recovery methods, clinker–cement ratio, raw materials and fuels (Plaza et al. 2020). The cement industry has the potential for significant carbon mitigation through various methods, including waste heat recovery (WHR), carbon capture, low-carbon fuels and blended cement. However, the effectiveness of these methods varies depending on the individual parameters of each cement plant and region. Despite their potential, adopting these mitigation methods is hindered by their capital-intensive nature and existing policies have not successfully promoted their uptake by the cement industry.

For example, in the excerpts mentioned, SD was used to analyze CO_2 emissions by examining the causes and prospects for lowering urban carbon emissions (Feng et al. 2013; Gu et al. 2019) and industrial carbon emissions (Onat et al. 2014; Proaño et al. 2020). This helped to understand the potential for CO_2 emission reduction while considering various parameters like energy usage, technological progress and policy regulations. The comprehensive and cause-and-effect-oriented nature of the approach led to numerous applications in studying the effects of GHG mitigation policy and project applications in particular fields, including energy (Feng et al. 2013; Sun et al. 2016; Saysel and Hekimoğlu 2013; Robalino-López et al. 2014), iron and steel (Kim et al. 2014), transportation (Procter et al. 2017; Han and Hayashi 2008; Han et al. 2008; Barisa and Rosa 2018) and cement industries (Ansari and Seifi 2013; Anand et al. 2006; Sheheryar et al. 2021; Junianto et al. 2023; Nehdi and Yassine 2020).

Kunche and Mielczarek (2021) reviewed and discussed various articles on carbon emissions reduction strategies, particularly within industrial sectors such as the cement industry. Relevant articles are identified and then included or excluded based on specific criteria, with several mentioned that employ system dynamics models in looking at sustainable practices and CO_2 emissions. Their studies did not have the techno-economic possibility of emission mitigation in this industrial sector. Therefore, this review discusses and analyzes the existing work on the SD modeling application and the effectiveness of various carbon mitigation strategies, especially in the cement industry.

Methodology

Due to a limited review articles published on carbon emissions mitigation strategies for the cement industry using SD, we reviewed only articles published in a margin of 10 years (2000–2023) to gather the scientific literature.

Identification of relevant articles

The study begins by identifying relevant articles through a comprehensive search process following PRISMA guidelines (Moher et al. 2009), as shown in Fig. 5. We searched for the words "system dynamics," "GHG mitigation OR "GHG reduction," "policy evaluation," "CO_2 reduction," "cement production" and "cement industry" using multiple databases. We used truncated words to capture different spellings and variations of the keywords and our search resulted in 1800 articles. After removing duplicate articles, unpublished articles and non-English materials, we screened the remaining studies by reading the titles, abstracts and keywords to ensure that they met the inclusion criteria. Then, we applied the exclusion criteria to select a portfolio of studies for more detailed review and analysis.

Selection criteria

The selected articles are chosen based on specific criteria. Papers that do not focus on particular models for the cement industry are excluded. The studies vary in research focus, modeling approach and geographical scope, indicating that a diverse range of articles is considered. This review only included articles that use the SD modeling approach to study CO_2 emissions in the cement industry, specifically focusing on addressing CO_2 reduction, policies, assessment or GHG mitigation objectives.

Data collection

The study collects research on policies, strategies and GHG emissions reduction regulations in the cement industry through database search engines. The collected documents primarily consist of academic papers published in peer-reviewed journals, indicating a focus on credible and peer-reviewed sources. It did not exclude articles based on journal rankings, as the review aimed to provide a comprehensive overview of SD models of cement carbon mitigation strategies.

Number of identified articles

The search process results in identifying articles matching the specified keywords. The review identified 12 articles on using SD modeling for GHG mitigation, policy evaluation and CO_2 reduction in the cement industry, as shown in Table 1.

In summary, the systematic approach followed in this study involves a comprehensive search using specific keywords and databases, a time frame, selection criteria, and an acknowledgment of variability in the selected articles. These are essential elements in conducting a rigorous and well-structured systematic literature review.

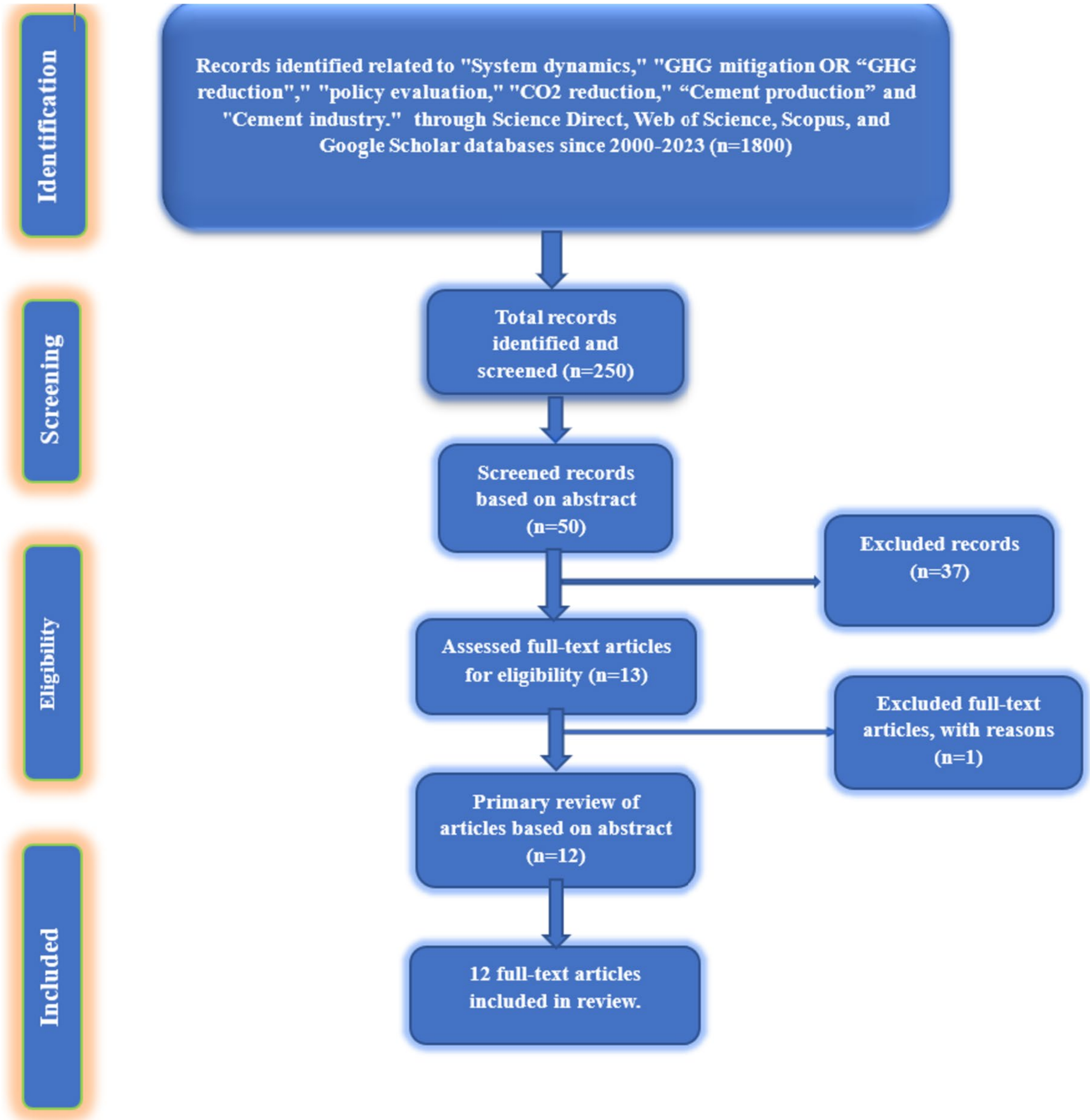


Fig. 5 Flowchart of literature review for cement GHG mitigation strategies using system dynamics according to PRISMA (Moher et al. 2009; Mengist et al. 2020)

Carbon mitigation methods

Technologies for mitigating CO_2 emissions in the cement industry

Cement production emits CO_2 from several sources, but mainly through burning fossil fuels and the calcination of limestone ($CaCO_3$) (Shahzad et al. 2017). Heating $CaCO_3$ at 1000 °C transforms it into lime (CaO) and further heating at 1450 °C forms clinker, an essential constituent in cement (Shahzad et al. 2017). Electricity usage for raw materials transportation and operating electrical motors contributes to indirect emissions (Attari et al. 2016; Rasheed et al. 2022). Direct emissions account for about 90% of CO_2, while raw material transport and other processes comprise 10% (Mikulčić et al. 2013; Daehn et al. 2022). One kg of clinker produces 0.5 kg of CO_2 during calcination (Worrell et al. 2001) and the process requires substantial thermal energy and electricity for burning and grinding the cement. This review considers these five leading CO_2 reduction technologies in the cement industry as classified by the IEA (2018, 2009, 2021), clinker substitution, alternative fuels, energy efficiency improvements, CCS and WHR. However, due to their ongoing development, Novacem and Geopolymer

Table 1 List of articles found in databases within cement mitigation strategies using SD

Authors/References	Application studies and results
Junianto et al. (2023)	This study used an SD model to simulate sustainable CO_2 emission reduction in the Indonesian cement industry until 2050. The results showed a genuine target for sustainable CO_2 reduction by 2050 would be a 27% decline compared to the 2020 baseline. This reduction can be accomplished by implementing carbon taxes, increasing alternative fuel use, adopting renewable energy sources and integrating CCS technology within cement plants
Sheheryar et al. (2021)	The study discusses the potential of ultrahigh-performance concrete (UHPC) as a sustainable alternative to Portland cement. The work highlights that UHPC, with its higher mechanical strength and longer service life, can potentially reduce CO_2 emissions from cement and concrete production by over 17% over a specific simulation period. Developing an SD model allows for testing different policy scenarios and provides a flexible framework for users to input and update data without reconstructing the entire model
Nehdi and Yassine (2020)	The paper introduces a novel SD model that addresses the complexity of CO_2 emissions from cement production and explores the potential of alkali-activated materials (AAMs) as a solution. The model considers various factors such as AAM type, concrete life span, carbonation, market share and policy implementation, enabling the identification of strategies to reduce emissions and informing decision-making processes at a low computational cost
Proaño et al. (2020)	The study used the SD to evaluate an indirect carbonation CCU method to reduce CO_2 emissions in the cement industry. The technical assessment indicates that carbonation processes involving sodium (Na) and barium (Ba) hydroxides are viable options with high efficiency in capturing CO_2. However, the Ca-based process is not practical. Furthermore, the economic analysis indicates that implementing the NaOH and Ba(OH)2 carbonation technologies may reduce cement plants' profits. However, the introduction of a CO2 tax could promote the adoption of CO2 capture technologies
Ekinci et al. (2020)	This study focuses on the impact of cement production on air pollution in an urban area. It develops a comprehensive model incorporating various variables and environmental factors affecting cement production and air pollution. The findings suggest that the PM_{10} pollution level is expected to increase above the critical level set by the World Health Organization, highlighting the need for government intervention and sustainable decision making in the cement industry to protect air quality
Tang et al. (2020)	This paper proposes an SD model to analyze the optimal path for reducing carbon emissions in a regional industry by considering regional differences and inter-regional contexts. The model is applied to the cement industry in Chongqing, China, demonstrating that leveraging regional collaboration and industrial chain integration can help achieve low-carbon targets. The findings suggest that this approach applies to other industries with shared regional demand markets, such as energy, chemical and steel
Jokar and Mokhtar (2018)	This research centers on analyzing the Iranian cement industry. It examines the effects of three energy efficiency measures (clinker substitution, WHR and alternative fuel use) in promoting sustainability between 2015 and 2034. Simulation results indicate that implementing clinker substitution could reduce energy consumption costs and CO_2 emissions by 13% and 11%, improving the trade balance through increased fossil fuel exports. However, installing waste heat recovery less impacts CO_2 mitigation but can enhance manufacturer profit by 4.5%
Vargas and Halog (2015)	The study explores the possibility of employing the SD method of using SCMs, such as FA, to reduce CO_2 released during cement production. It highlights the need to upgrade FA to meet the standards required for clinker substitution in cement blends. However, it also recognizes that the upgrading procedures may result in additional CO_2 emissions, which can offset the overall reduction achieved. An SD model was introduced to quantify the net CO_2 reduction. The model demonstrates that by utilizing ultra-fine grinding, which consumes 0.75 GJ/tonneFA of energy compared to the baseline cement emissions, achieving an impressive 80% reduction in CO_2 emissions becomes feasible
Song and Chen (2014)	This study proposes a simulation model using SD to analyze and forecast emission trends in the cement industry, considering energy conservation and emission reduction targets. The model provides decision makers with valuable insights into the current emission situation and enables precise prediction of future emission trends, contributing to achieving emission targets in the Chinese cement industry
Ansari and Seifi (2013)	This study introduces an SD model that examines how energy price reform influences energy consumption and production in the cement industry. The model considers different scenarios for production and export, as well as factors like cement demand, energy consumption, production levels and CO_2 emissions. The result showed that removing energy subsidies and implementing corrective measures within the industry. Also, the model predicts a 29% reduction in natural gas consumption, a 21% reduction in electricity consumption and a 22% reduction in CO_2 emissions
Anand et al. (2006)	This study used an SD model to calculate approximately the amount of CO_2 released by the cement industry in India. The model considers various policy options, population growth, structural management and energy saving of cement production processes. According to the projections, implementing these policies can result in a significant 42% decrease in CO2 emissions by 2020. The study also included the indirect CO_2 emissions associated with transporting raw materials and finished cement products

Table 1 (continued)

Authors/References	Application studies and results
Nehdi et al. (2004)	The study examines the requirement for a dependable tool to predict the effects of extensively replacing Portland cement with SCMs on CO_2 emissions within the cement industry. The authors suggest a new system dynamics model that enables the examination of various scenarios and tackles the complex nature of the CO_2 emissions challenge in cement production. This model provides a flexible and adaptable framework for policy formulation and testing

cement mitigation technologies are not included. The following sections will introduce these technologies and provide essential information for our study.

This review considers these five leading CO_2 reduction technologies in the cement industry as classified by the IEA (2018, 2009, 2021). These include clinker substitution (Blended Cement), using alternative fuels (Fuel Switching), energy efficiency improvements, CCS and WHR. We will provide essential information on each of these technologies. However, due to their ongoing development, this study does not cover other CO_2 mitigation technologies or production measures, such as Novacem or Geopolymer cement. The following sections will introduce these technologies and provide essential information for our study.

Alternative materials (Clinker substitution)

As we attempt to reduce global CO_2 emissions, it is essential to address the significant contribution of the cement industry. Using supplementary cementitious materials (SCMs) as alternative materials offers a sustainable solution to reduce CO_2 emissions in the cement industry (Rhaouti et al. 2023; Sirico et al. 2020; Abubakar et al. 2021). One of the most promising mitigation strategies for reducing carbon emissions in the cement industry is substituting clinker cement with SCMs or reducing the amount of clinker, which is the primary component of blended cement in cement production (Suraneni 2021; IEA 2021). This method can be accomplished by using additives in the cement blend, which requires less energy and reduces the clinker requirements per ton of cement (Taylor et al. 2006). Blended cement production offers a solution to mitigate carbon emissions and high energy consumption related to clinker production (Ige and Olanrewaju 2023). Replacing a portion of the clinker with SCMs, such as industrial by-products like coal fly ash or blast furnace slag (Osmanovic et al. 2018; Tao et al. 2022; Dandautiya and Singh 2020), lowers the clinker/cement ratio without compromising the properties of Portland cement. This reduces the clinker/cement ratio (Ali et al. 2011), reducing emissions from energy consumption in the kiln and process emissions from clinker production (Taylor et al. 2006). This process can reduce CO_2 emissions by at least 5% and up to 20% of total emissions from cement production worldwide (Ali et al. 2011; Koytsoumpa et al. 2018; Bosoaga et al. 2009).

Switching to alternative fuels

Fuel switching to lower-carbon alternative fuels is another potential method for mitigating CO_2 emissions (Chatziaras et al. 2014). Alternative fuels involve substituting traditional fossil fuels such as oil, coal and pet coke with more environmentally friendly options, reducing carbon emissions during cement kiln combustion (Georgiopoulou and Lyberatos 2018; Usón et al. 2013). The cement industry ranks as the third-largest consumer of energy among industrial sectors (Agency 2014). The use of waste-derived alternative fuels, such as refuse-derived fuels (RDF) or used tires, has gained popularity in the cement industry due to rising fossil fuel costs, depletion of resources and increased environmental awareness around use of fossil fuels (Rahman et al. 2013; Georgiopoulou and Lyberatos 2018). Using alternative fuels in cement production offers an opportunity to reduce long-term carbon emissions, waste disposal and reliance on fossil fuels (Tsiliyannis 2018; Tun et al. 2021). However, incorporating waste materials as alternative fuels can affect cement quality and potentially increase emissions of harmful volatile elements like mercury and thallium (Rahman et al. 2013; Horsley et al. 2016). Furthermore, using waste materials as alternative fuels can reduce dependence on fossil fuels, lower production costs in cement manufacturing and decrease CO_2 emissions (IEA 2018; Habert et al. 2010). Alternative fuels such as natural gas, biomass and waste-derived fuels like sewage sludge, tires and municipal solid waste can reduce indirect emissions from fossil fuel combustion (Çankaya and Pekey 2018).

Energy efficiency improvement

Improving energy efficiency is vital to reducing CO_2 emissions from fuel and cutting down the cost of cement production by optimizing fuel and electricity use. One approach is to use energy-efficient equipment and replace outdated installations. Improving fuel efficiency is vital for reducing energy input in cement production, as most energy consumption is attributed to the heat generated by the large rotary kiln. Also, switching from the wet to the dry process can significantly improve energy efficiency, as the dry process with pre-heaters and pre-calcination is more efficient (Huang and Wu 2021; Zuberi and Patel 2017). Switching to the dry process with calciner, as outlined in the CSI's Getting the Numbers Right Protocol (Initiative 2009), can reduce energy consumption by up to 50% and decrease CO_2 emissions by 20%. Process upgrading can also include optimizing the clinker cooler, improving preheating efficiency, enhancing burners and implementing advanced process control and management systems (Hasanbeigi et al. 2013). Therefore, implementing this mitigation strategy requires a substantial financial commitment, with the period for achieving a return on investment directly linked to the current market price of cement.

Carbon capture and storage potential in the cement industry

CCS is a recent mitigation method that uses chemical solvents to suck up CO_2 from exhaust flue gases and can potentially reduce emissions in the cement industry by 65–75% (Anderson and Newell 2004). It captures and compresses CO_2 emissions into liquid form for transport to underground storage facilities. While not yet widely implemented, CCS is suitable for industries with other alternative technologies to reduce carbon emissions in cement production. The impact of emissions on climate change drives the development of advanced energy cycles incorporating CO_2 management; according to the Carbon Capture and Storage Association (CCSA) (Capture and Association 2016), CCS can capture up to 90% of CO_2 emissions from industrial processes that uses fossil fuels, preventing their release into the atmosphere. CCS includes three technologies: pre-combustion, post-combustion and oxy-fuel combustion capture. Pre-combustion capture is considered less promising than post-combustion and oxy-fuel combustion due to its inability to capture CO_2 during the calcination process and the need for modifications in clinker burning to handle pure hydrogen's explosive properties (IEA 2009).

Additionally, the by-products generated during the process would require transportation and disposal, resulting in extra costs (Proaño et al. 2020). However, due to its novelty, the implementation costs of CCS are significantly higher than those of other mitigation methods listed. According to IEA (2018), most CCS technology is tested through pilot projects currently and oxy-fuel capture technologies are not yet proven commercially. The CCS can reduce GHG emissions emitted by cement plants by 65–80% despite its potential not being fully explored (Wei and Cen 2019). Once again, CCS technology has many disadvantages, such as high costs (Benhelal et al. 2013), excessive energy use, CO_2 leakage (Haszeldine 2009) and the cost of capturing 1 ton of CO_2 equivalent to the price of 1 ton of cement in China (Wei et al. 2015). Although CCS technologies have the potential to reduce emissions significantly, it faces technological and economic challenges in many cement industries (Leeson et al. 2017; Bahman et al. 2023).

Waste heat recovery (WHR)

Waste heat in cement production mainly comes from the clinker cooler discharge and kiln exhaust gas, representing 35% of total energy (Khurana et al. 2002). These waste heat sources can be harnessed to generate electricity through steam turbines, reducing the need for purchased electricity and overall electrical demand. The average flue gas temperature from the cement kiln is about 1200 °C and is used in pre-heaters to improve the specific energy consumption. The exhaust gas temperatures, ranging from 250 to 450 °C, leaves the pre-heaters and contain sufficient thermal energy for electricity generation using a Rankine cycle, thereby reducing electricity purchased (Pili et al. 2020; Madlool et al. 2011). The success of WHR in reducing carbon emissions and ensuring financial stability depends on factors like grid emission factor, electricity prices and plant utilization rate. WHR systems can generate around 30–45 kWh/ton clinker in larger cement kilns (Schneider et al. 2011). However, the efficiency of WHR steam needs to be estimated by considering internal losses and energy transfer inefficiencies (Madlool et al. 2011). Insulating the outer surfaces of cyclones and ducts can also improve energy efficiency by reducing heat loss through convection and radiation from the kiln's hot surfaces. WHR is a promising, cost-effective technology (Moya et al. 2011). As a result, all these five mitigating technologies must be used to meet CO_2 reduction goals. Over 16 years, from 1990 to 2006, the cement industry has reduced its thermal energy usage from 3605 to 3382 MJ/T clinker by approximately 6% (Mehta 2010). Using slags and fly ash as part of clinker production to reduce carbon emissions also reduces electric energy efficiency.

System dynamics in the cement industry for GHG mitigation

Cement production requires substantial investments and its production costs depend on various factors like raw materials, fuel, labor, transportation and taxes. The life span of cement plants makes their financial sustainability sensitive to changes in these factors (Boyer and Ponssard 2013). Carbon mitigation strategies like WHR and CCS can reduce GHG emissions, but their effectiveness depends on local electricity emissions and fuel properties. Implementing these strategies can impact production costs by changing fuel and electricity usage, changing various tax scenarios and generating additional income, improving return on investment and making these mitigation strategies more attractive for implementation (Doğan et al. 2018). Neglecting important feedback in decision making may lead to policy resistance (Sterman 2002). Therefore, utilizing an SD model can assist stakeholders in making informed decisions and exploring various policy options. SD models are increasingly used to predict carbon emissions in various industries, but their application in the cement sector is limited. The methodology section presents an overview of relevant studies that used SD to forecast emissions or assess mitigation strategies/policies in the cement industry. The selected studies are analyzed based on evaluated mitigation methods, study scope, modeling dimension and experimental settings.

Junianto et al. (2023) used an SD model tool to predict and evaluate CO_2 emissions reduction targets in the Indonesian cement industry until 2050. They incorporated input from stakeholders and expertise to forecast practical implementation strategies and focused on variables that affect CO_2 emissions in the cement industry. The study used scenarios formulated through an analytical hierarchy process with stakeholders and introduced variables as mathematical relationships. The model was validated using the absolute mean error (AME) method and CO_2 emission data published by the Indonesian Ministry. The results showed that a network of interconnected factors, including population growth, cement production and demand, clinker production, traditional fuel consumption, electrical energy and CCS technology implementation, would lead to a 27% reduction in emissions compared to the 2020 baseline.

Sheheryar et al. (2021) used the SD model to investigate the potential reduction in carbon emissions by replacing Portland cement (PC) with Ultra-High-Performance Concrete (UHPC) in the concrete industry. The SD model consisted of four sectors: cement demand, PC, UHPC and CO_2 emissions, and employed a single stock–flow structure to assess the feasibility of this approach. The authors developed multiple scenarios to simulate different policies and explore the environmental impact of substituting UHPC for PC using Stella software. The authors tested different policy scenarios and highlighted a nonlinear correlation between the percentage of PC replacement and the extent of emission reduction. The results showed that UHPC could reduce cumulative CO_2 emissions of cement and concrete by over 17% during the studied simulation period. However, the effectiveness of UHPC in reducing CO_2 emissions depends on various future policy scenarios. Overall, the results suggest that UHPC has the potential to reduce CO_2 emissions in the concrete industry significantly, but the outcome depends on various future policy scenarios.

Nehdi and Yassine (2020) developed an SD model to predict CO_2 emissions in the cement industry over the next three decades. The model incorporates the feedback from the increasing use of alkali-activated materials (AAMs) and their impact on the market share of PC. The model comprises five sectors: forecast, carbonation, PC and AAM concrete, CO_2 emissions and AAM composition. The study investigates various parameters related to AAMs, such as activator type, precursor type, policy implementation period, AAM carbonation rate, total AAM market share and AAM concrete service life. The study utilized four scenarios to test the impact of different policies on net emissions released. The purpose of the model is to serve as a tool for policy testing and evaluating how substituting cement with AAMs could potentially affect CO_2 emissions. The study extensively examines the production process of eco-efficient AAMs, including production techniques, curing and placement techniques, carbonation, aging and life cycle performance. The authors also conducted a sensitivity analysis to assess the influence of AAM carbonation and service life. The authors did not mention the validation method used. The model provides decision makers and policy makers with an efficient means to evaluate the impacts of AAMs on CO_2 emissions from cement production while minimizing computational requirements.

Proaño et al. (2020) used an SD to assess the techno-economic impact of employing indirect carbonation CO_2 capture technology to reduce CO_2 emissions in clinker production. Their model incorporates various subsystems, including cement production and demand, CO_2 estimation and capture, and costs and profit, to simulate the financial implications of implementing carbon capture in cement production. The authors consider the carbon capture method and the impact of additional investment costs, which are vital factors influencing mitigation adoption rates in the cement industry. The authors adopted the SD approach to deal with the challenges of modeling economic behavior that depends not just on initial investment and operating costs, market conditions and government policy that change over time. The model was assessed and validated at each stage of development, including structural verification using historical data on GDP and cement demand. The study considers different technical scenarios, evaluating the effectiveness of employing sodium, barium or calcium-based solvents in the carbon capture module for mitigating CO_2 emissions. The model uses 11 stocks and 14 flows represented in stock-and-flow diagrams. The study used a structural verification test and historical data from clinker and cement production to validate the model. The study concludes that implementing a carbon tax would significantly encourage the use of carbon capture technologies and help the cement industry achieve its emission reduction goals.

Ekinci et al. (2020) adopted a holistic approach to identify the factors influencing cement production and the environmental factors contributing to urban air pollution using an SD model that incorporated real-time data to assist decision makers in proactively protecting the environment. The study highlights the interconnection between industry, such as population growth and construction demand, aiming to include all external factors that indirectly contribute to pollution in the cement industry. However, the model lacks detailed calculations of emissions from specific modules in the cement production process, such as clinker production, fuel consumption and electricity. The study also analyzed some strategic-level decisions to reveal their environmental impact. Cement industry emissions were calculated based on yearly GDP and construction activity, considering cement production capacity, distinguishing it from other studies in the field. The authors did not provide a stock-and-flow diagram or parameter list to assess the complexity of the model and a one-way ANOVA test was used to validate the simulation results. The study establishes a correlation between the need for new construction, cement production and regional air pollution, but it lacks a clear outline of the different subsystems employed in their SD model.

Tang et al. (2020) simulated long-term energy demand, energy consumption, cement production and CO_2 emissions in China's Chongqing region's cement industry using a system dynamics (SD) model. The study incorporated regional differences and inter-regional factors, considering technological and comparative industrial advantages among neighboring areas. The simulation covered the period from 2018 to 2030. The SD model focused on three subsystems: demand, supply and emissions within the regional CO_2 emission system. They conducted a case study on the cement industry in Chongqing, simulating two scenarios: business as usual (BAU) and low-carbon consumption. The study assumed increased clinker substitution, improved electricity efficiency and improved production capacity as measures to reduce carbon emissions. They include utilization ratios for clinker substitutes, fuel substitutes and waste heat recovery (WHR) as exogenous parameters, which vary based on the specific scenario under investigation. The model assumed a constant policy scenario throughout the simulation and was validated using dimensional consistency tests, structural verification and historical data before performing sensitivity analyses rate on the WHR utilization, emission intensity, clinker ratio and alternate fuel use.

Jokar and Mokhtar (2018) developed an SD model to examine the sustainability impact of three energy efficiency measures on the Iranian cement industry. The model included economic and social subsystems, evaluating producer profit and market pricing and consisted of six subsystems: cement and clinker production, energy consumption, CO_2 emissions, economic analysis and social evaluation. The study employed 5 stocks and 10 flows based on stock-and-flow diagrams. The authors validated the model using historical data and performed a sensitivity analysis on production costs. This model improves upon previous ones by incorporating economic and social considerations in assessing mitigation strategies and estimating employment requirements. The study revealed that clinker substitution can reduce CO_2 emissions and energy consumption costs by 13 and 11%, respectively, while waste heat recovery (WHR) benefits producer profits and labor participation. Also, the result showed more opportunities for fossil fuel exportation, improving the country's trade balance.

Vargas and Halog (2015) employed an SD methodology to explore the potential benefits of utilizing fly ash as a substitute for clinker in cement production to reduce CO_2 emissions. They conducted simulations of five life cycle scenarios for cement incorporating varying proportions of upgraded fly ash (20 and 35%) to assess the resulting net reductions in CO_2 emissions. The SD model includes this extra energy use when analyzing CO_2 emissions. The model consists of 5 stocks, 5 flows and 14 converters to evaluate and compare the emissions with a cement plant with an upgrading process and without upgrading processes. The authors do not state the model validation process and the parameter values used are not specified, but their results were sensitivity analyzed. This simulation confirms what was found in the earlier study, namely that both fly ash and upgraded fly ash reduce cement industry emissions. The result showed that upgrading processes produced additional emissions, decreasing the reductions realized using FA.

Song and Chen (2014) employed an SD approach dynamics simulation model to predict future emission trends within the Chinese cement industry. The model considers energy-saving and emission–reduction goals and incorporates five optimization scenarios: demand reduction, technological advancements, fuel substitutions, material substitution and waste heat power generation. The model identifies key strategies for reducing GHG emissions in the cement sector by analyzing these factors. The goal is to explore various energy supply options, technology alternatives, and policy benefits through a predictive model in Stella software to reduce GHG emissions. The model undergoes rigorous verification and validation and processes to ensure its accuracy. The authors suggest that their results may assist decision makers in identifying the current emission scenario, accurately forecasting emission trends and achieving emissions targets while considering the entire cement production process in China. Ultimately, this can assist in achieving emissions targets.

Ansari and Seifi (2013) used an SD model to investigate the impact of energy price subsidy reform on energy consumption and CO_2 emissions in the Iranian cement industry. Their investigation involved exploring different production and export scenarios, considering updated energy prices. The model incorporated various factors, including cement demand, production, energy consumption and CO_2 emissions, focusing on directly utilizing natural gas to analyze the effects of subsidy reforms on fuel and electricity in the cement industry and explore potential corrective policies, such as blended cement and waste heat recovery (WHR), to mitigate carbon emissions. They indicated that the model employs 51 parameters, of which 34 are endogenous and 17 are exogenous. The authors utilized historical data to validate the model, including factors such as GDP growth rate, fuel and electricity prices, and natural gas utilization rate. The simulation results suggest that removing all energy subsidies and implementing corrective measures in the cement sector can reduce electricity consumption by 21% and natural gas by 29% and reduce emissions of CO_2 by 22%, based on each scenario's energy demand simulated outlook.

Anand et al. (2006) developed a model to assess the reduction of CO_2 emissions in the Indian cement sector under different mitigation scenarios using system dynamics. The model considers various mitigation scenarios and emphasizes the influence of population growth and GDP on cement demand and resulting carbon emissions reduction. The model incorporates thermal waste heat recovery (WHR) alongside blended cement as a mitigation method and does not include the energy prices and the production capacity dynamics expansion. The study generated three scenarios baseline scenarios (BS) and modified scenarios categories. The study used structural verification, historical data and dimension consistency tests to validate the model and conducted a sensitivity analysis on cement demand, considering the impact of GDP and population. Moreover, the model assumes that only coal is a thermal energy source utilized in clinker production, with no consideration given to other mitigating methods like alternative fuels and addressed only the impact of thermal WHR and efficiency improvements neglecting potential mitigation methods like alternative fuels or electrical WHR.

Nehdi et al. (2004) conducted a study using an SD model to examine the potential of clinker substitutes, such as SCMs, to reduce CO_2 emissions within the cement industry. The model assumes that cement consumption is affected by the GDP growth rate in developing nations and the population in developed countries. The model comprises five sectors: Forecast, FA concrete, Slag concrete, PC concrete and CO_2 emissions to simulate various policy measures. The study included two additional simulation scenarios to calculate the availability of slag and fly ash, which are by-products from sectors like the steel industry and coal power plants. Although the authors did not explicitly state their model validation method, they simulated the results across multiple scenarios. The results indicated that blended cement could reduce CO_2 emissions in the cement sector.

Discussion

Studies found within cement mitigation strategies using SD

Through the literature search, 12 relevant documents were identified, as shown in Table 2. All 12 studies analyzed methods to reduce GHG emissions within the cement industry. Additionally, two studies analyzed the economic impact and eight analyzed policy options. For a model to be considered an effective tool for decision making and analysis, it should enable the evaluation of the most promising mitigation techniques that are presently accessible in the cement industry. In the cement industry, the model's scope largely depends on its usefulness to stakeholders accountable for decision making. Including an economic analysis of mitigation project implementation in models is essential for decision making. Different dynamic factors, for instance, energy and maintenance costs, can impact the payback periods for the capital investment required in mitigation projects.

Theoretical and practical implications of cement mitigation strategies using SD

Most research has centered on mitigating strategies to reduce carbon emissions in the cement industry using SD without establishing a connection between these measures and a plan of action for policy implementation. In Table 2, none of the studies included all available technologies for reducing the impact of the cement industry on the environment based on the IEA's classification. Only Junianto et al. (2023) and Proaño et al. (2020) included the CCS mitigation method from the 12 studies reviewed.

Ansari and Seifi (2013) did not consider alternative fuels, while Nehdi and Yassine (2020), Sheheryar et al. (2021), Nehdi et al. (2004) and Vargas and Halog (2015) focused only on alternative materials. Proaño et al. (2020) analyzed only the effects of the carbon capture method. Junianto et al. (2023) omitted WHR and Jokar and Mokhtar (2018) did not address efficiency improvements. Only Sheheryar et al. (2021), Jokar and Mokhtar (2018) and Proaño et al. (2020) included economic evaluation or cost estimation models in their studies, while others mainly focused on predicting carbon emissions, as summarized in Table 2.

Furthermore, apart from Proaño et al. (2020) and Vargas and Halog (2015), all the models discussed in this paper simulate the impact of CO_2 mitigation projects on the entire cement industry, which is suitable for assessing overall consequences in a vast area from the view of

Table 2 Summary of the mitigation methods highlighted in the literature review using SD within the cement industry

References	Model validation	Software	Study description	Clinker substitution	Alternative fuels	Energy efficiency improvement	WHR	CCS
Junianto et al. (2023)	Yes	Powersim	Cement demand, population, growth, cement production, traditional fuels, clinker production, electrical energy and CCS technology	✓	✓	✓		✓
Sheheryar et al. (2021)	None	Stella	Cement demand sector, OPC Sector, UHPC sector and CO_2 emissions sector	✓				
Nehdi and Yassine (2020)	None	Vensim	Forecast sector, OPC sector and AAM concrete sector, carbonation sector, CO_2 emissions sector and AAM composition sector	✓				
Proaño et al. (2020)	Yes	Aspen Plus	Cement production, CO_2 estimation, Cement demand, capture costs and profit					✓
Ekinci et al. (2020)	Yes	Stella						
Tang et al. (2020)	Yes	Vensim	Demand, supply and emission	✓	✓		✓	
Jokar and Mokhtar (2018)	Yes	Vensim PLE	Clinker production capacity, cement production capacity, CO_2 emissions, energy consumption, economic module, social module	✓	✓		✓	
Vargas and Halog (2015)	None	Ithink		✓				
Song and Chen (2014)	Yes	Stella	Demand reduction, material substitution technological progress, waste heat power generation and alternatives fuel	✓	✓	✓	✓	
Ansari and Seifi (2013)	Yes	Ithink	cement demand, production, energy consumption and CO_2 emissions,			✓		
Anand et al. (2006)	Yes	Powersim	Demand and production, Energy consumption, Availability of slag and fly ash, CO_2 emissions from cement plants, CO_2 emissions arising from transport requirements	✓	✓		✓	
Nehdi et al. (2004)	None		FA concrete, forecast, slag concrete, PC concrete and CO_2 emissions	✓				

policy makers. This approach can help examine mitigation strategies' impacts on the cement industry on a broad level, suitable to policy makers but lacking flexibility for stakeholders in the industry.

Many cement companies typically operate only one production plant and the availability and costs of mitigation resources vary among these plants (Edwards 2017). Previous studies have neglected the interactions between different mitigation methods. For instance, in plants where substitute materials like blast furnace slag and fly ash are already replacing a fraction of their clinker, the quantity of heat produced during clinker production fluctuates based on the changes in the substitution percentage and plant operation rate. This variation directly impacts the amount of electricity that can be produced through WHR. Since the availability and cost of resources for mitigation, such as furnace slag, fly ash, or refuse-derived fuels as a fuel alternative, may differ from plant to plant, companies with more than one plant often make decisions regarding mitigation projects based on their plants.

The studies by Jokar and Mokhtar (2018), Ansari and Seifi (2013) and Anand et al. (2006) do not consider the input conditions for calculating the energy recovered while addressing WHR mitigation. Many factors play a role in cement plants not operating at maximum capacity, which would significantly impact the amount of energy recovered or gained by WHR. For reference, in 2021, India's average utilization share of the cement industry was 52.4%, with variations between individual cement plants. Except for Proaño et al. (2020), previous studies ignore the impacts of carbon capture, a new mitigation strategy that uses indirect carbonation to capture CO_2 from exhaust gases under different market scenarios and a CO_2 tax economic policy.

Most recent research has focused on mature technologies, such as energy efficiency and alternative fuels, clinker substitutes, etc., to reduce carbon emissions from cement plants. They are easy to implement because they are cost-effective and have public data. However, innovative and emerging technologies, such as WHR, require adequate funding from the government, motivation and research and development efforts. Most reviewed studies have concentrated on mitigating strategies, technical possibilities and developing plans for carbon reduction in the cement industry without linking these measures to a specific plan of action for policy implementation. The requirements and feedback from mitigation methods, which would significantly affect the feasibility of the projects, have overlooked the importance of considering in earlier studies. The main concern of stakeholders in the industry is to assess the economic feasibility of implementing mitigation measures, as methods such as efficiency improvements and WHR require considerable investment that may affect profit margins. As a result, the absence of research on scenarios involving adopting multiple mitigation approaches with varying implementation costs hinders experimentation in this area.

The techno-economic feasibility of emission mitigation strategies in the cement industry

The techno-economic feasibility of carbon emission mitigation strategies in the cement industry depends on various factors, such as the availability and cost of alternative materials, fuel sources, technologies and the market price of cement. Additionally, market conditions and the financial investment required influence the payback period for implementing these mitigation strategies. Also, the industry depends on various factors, including the specific strategies being considered, the geographical location of the cement plants, the regulatory environment and the state of technology. This assessment is a valuable tool for investors and decision makers in determining mitigation strategies' feasibility. This topic is crucial as cement production contributes significantly to industrial carbon emissions (Kunche and Mielczarek 2021). Therefore, it is essential to assess the techno-economic feasibility of these strategies to determine their viability and potential impact on carbon emissions in the cement industry. Implementing these mitigation strategies in the cement industry is technically and economically feasible. Adopting various measures such as improving energy efficiency, clinker substitution, waste heat recovery, and carbon capture and storage reduces CO_2 emissions in this sector significantly (Shen et al. 2021). The cement industry has the potential for significant carbon mitigation through these methods.

However, the effectiveness of these methods varies depending on the individual parameters of each cement plant and region. Despite the availability of various mitigation options, their adoption rates in the cement industry have been inadequate. One of the strategies for carbon emission mitigation in the cement industry is improving the efficiency of energy usage. This involves optimizing fuel and electricity use in cement plants, which can significantly reduce CO_2 emissions. This strategy holds great potential for reducing carbon emissions in cement production (Fadayini et al. 2021), contributing to the industry's sustainability and helping meet global carbon emission reduction targets. Old cement plants can improve energy efficiency through equipment replacement and process optimization (Kunche and Mielczarek 2021). Implementing waste heat recovery systems in cement is a technologically and economically feasible carbon emission mitigation strategy. It involves capturing and utilizing waste heat generated during cement production, reducing energy consumption and associated carbon emissions. Furthermore, clinker substitution with alternative materials, such as fly ash or slag, is also a viable option for reducing carbon emissions. The availability and cost of these alternative materials and the technical considerations related to their suitability for use in cement production play a crucial role in determining the economic feasibility of this mitigation strategy. In addition, using alternative fuels, such as biomass or refuse-derived fuels, or used tires as a substitute for traditional fossil fuels can significantly reduce the carbon intensity of cement production. Also, this strategy depends on the availability and cost of these substitute fuels. The potential reduction in CO_2 emissions from using alternative fuels in the cement industry can reduce impacts significantly (Hossain et al. 2017). Aside from improving energy efficiency, clinker substitution and the use of alternative fuels, another carbon emission mitigation strategy in the cement industry is the implementation of waste heat recovery systems.

Furthermore, implementing CCS technology in the cement industry is a promising method to reduce CO_2 emissions. This strategy involves capturing CO_2 from exhaust flue gases during cement production, storing it underground or utilizing it for other purposes. It has the potential to reduce CO_2 emissions significantly, estimated to be between 65 and 75% in the cement industry. These systems capture and utilize the waste heat generated during cement production, reducing energy consumption and associated carbon emissions. This technology in the cement industry shows promise as a carbon emission mitigation strategy.

Conclusion

The paper presented a comprehensive overview of how SD modeling evaluates strategies for mitigating carbon emissions according to the IEA's classification. It focused mainly on the cement industry and discussed emission reduction methods. The paper identifies gaps and improvements in CO_2 mitigation methods and then highlights the need for more research. This study addressed the application of SD models in assessing policies and predicting emissions in various fields, particularly emphasizing their application in the cement industry. The study also identifies gaps where earlier studies have not adequately addressed the topic. It suggests future research directions to enhance the effectiveness of using SD models to evaluate mitigation strategies. Considering the complexity and uncertainty in the cement industry's profitability, it is essential to use comprehensive system models. These models should assess the effectiveness of mitigation techniques and aid decision making. The scope of such models determines their usefulness to stakeholders. Models that include economic analysis are precious for decision making, as they consider dynamic factors like energy and maintenance costs that affect capital investment payback periods in mitigation projects.

According to the literature, SD modeling can assist policy makers and senior managers within the cement industry in evaluating the success of various GHG mitigation initiatives. The results suggest that policy changes can significantly reduce GHG emissions, resulting in CO_2 emissions reductions. The model helps identify preferred mitigation options under specific market conditions, informing policy decisions. The SD method has the potential to assist stakeholders in determining the optimal combination of mitigation methods that can balance the effectiveness of mitigation and overall profit margins by focusing on a single reference plant instead of the entire cement industry. According to the studies reviewed, SD modeling can be used to assess the effectiveness of policy interventions and technology-based interventions in the cement industry for reducing GHG emissions.

Similar to any other studies, this review has some limitations. Conducting a literature review can provide a comprehensive overview for identifying research gaps and evaluating existing knowledge within the field. Since this review focuses on various studies that use SD models to assess and compare different strategies to reduce carbon emissions within cement production, the details of each mitigation method could not be covered.

Earlier review studies on SD have primarily focused on quantifying CO_2 emissions and estimating potential reductions in the cement industry by adopting various corrective, structural and economic policies under different scenarios without establishing a link between these measures and a specific plan of action for policy implementation. Most of these measures primarily focus on cement production, demand and supply, energy consumption and CO_2 emission, neglecting the utilization of end-of-life stages of the cement life cycle. Additional research on policy scenarios, cost implementation and practical implementation viewpoints on CO_2 mitigation during the end-of-life stage of cement using SD is necessary for this field. Implementing SD approaches in this manner would be relatively effective in assessing plants' sustainability, helping to solve decision-making challenges. Further research in this area must include challenges in implementing these interventions, such as high costs, technological barriers and regulatory issues.

Author contributions OE was involved in writing—original draft preparation, methodology, data curation, investigation, validation, formal analysis. DVVK and DA helped in conceptualization, resources, supervision, writing—reviewing. DVVK and DA contributed to data curation, supervision, writing—reviewing and editing.

Funding Open access funding provided by University of Johannesburg.

Data availability Enquiries about data availability should be directed to the authors.

Declarations

Competing interest The authors have not disclosed any competing interests.

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