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Carbon footprint of the future cement industry in the Middle East and North Africa

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ABSTRACT

The carbon footprint of cement manufacturing in the Middle East and North Africa (MENA) area, both now and in the future, is thoroughly evaluated in this paper. The study measures greenhouse gas emissions from both direct and indirect sources at various cement supply chain stages using life cycle assessment (LCA) methodologies. To determine the most carbon-intensive processes and support regional sustainability initiatives, emission data from a few chosen MENA nations are examined. and contrasted, with a focus on the cement industry in Iraq. The study highlights the significant environmental burden of clinker production, which remains the primary contributor to emissions due to its high energy requirements. Through comparative analysis of cement types, the research demonstrates that blended cements such as CEM II, CEMIII, CEMIV, and CEMV offer substantial potential for emission reductions. The CO_2 emission reduction rates compared to CEM I are CEM II: 18% reduction, CEM III: 31% reduction, CEM IV: 17% reduction, CEM V: 34% reduction.The results emphasize the need for a comprehensive approach to decarbonizing the cement sector, including replacing materials and using alternative fuels, recording real emissions to find appropriate solutions, and regional cooperation. To achieve climate goals and implement low-carbon practices in cement trade in the Middle East and North Africa, policymakers, researchers and industry stakeholders can benefit from this study.

Keywords: life cycle assessment, environmental impact, global greenhouse gas emissions, carbon footprint.

INTRODUCTION

One of the most widely produced and utilised building materials is cement, which provides necessities such as housing and infrastructure. However, its production necessitates significant energy consumption, raw material resources, and adverse environmental repercussions (Georgiopoulou and Lyberatos, 2018). The process of making cement is intricate, involving high raw material consumption and energy demand, largely due to urbanisation and industrial development. The process involves three steps: transportation, production, and the acquisition of raw materials. Explosives are used to extract raw resources., which emit particulate matter. Transportation involves heavy trucks, high energy consumption, and vehicle emissions. The final stage is cement production (Kaygin, 2022). It is produced by crushing a mixture of natural limestone and clay at high temperature. The primary raw materials are limestone and clay, with lime, silica, alumina, and iron oxide present in specific quantities. The crushed raw material mixture, heated to high temperatures of up to 1500 °C, In order to extract semi-dissolved particles toward the bottom outlet end of the oven. Raw meal is baked in a rotary oven (Oktaysoy et al., 2022). The cement industry produces clinker, a spherical granular material, which is then mixed with plaster to adjust the time of cement production, resulting in Portland cement (PC). Different types of cement, referred to as improved cements, are created when clinker is ground with gypsum stones and mineral additives, such as slag, limestone dust, fly ash (FA),containing silica and aluminum oxide, reacts with calcium hydroxide during cement hydration, enhancing the strength and durability of concrete (Valderrama et al., 2012; Junaidi et al., 2025). The cement manufacturing process releases a reasonable amount of particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides (NOx), and carbon monoxide (CO). In addition to greenhouse gas emissions (Mahasenan et al., 2003; Ali et al., 2011; Karagiannidis, 2012; Schorcht et al., 2013). Not to mention the noise and the disposal of heavy metal-containing solid and liquid waste into aquatic habitats, which is extremely concerning because of the metals' high toxicity, stability, and abundance. Certain species acquire toxic levels, which have an impact on the food chain and human health. It is commonly known that the growing industrial and human activity is the primary cause of the significant increase in heavy metal concentrations in aquatic systems close to metropolitan areas (Hashim et al., 2018).The main factors that determine carbon dioxide emissions are the type of fuel and the industrial process (Gäbel et al., 2004). For example, carbon dioxide emissions from chemical reactions are approximately 0.53 tons CO_2eq per ton of clinker in the dry cement manufacturing process when using a five-stage preheater, a pre-calciner, and 100% petroleum coke as fuel (Georgiopoulou and Lyberatos, 2018). Recently, global cement production has increased significantly, reaching 4.13 million tons in 2016 and is expected to reach 4.68 million tons annually by 2050 (Brian et al., 2023). Concern about carbon emissions that contribute to climate change has intensified as a result of growing public knowledge of the dangers posed by global warming, as the atmospheric concentration of carbon dioxide currently surpasses 380 parts per million (Sabine et al., 2004). Climate change is a growing global threat, and strategies to mitigate GHG emissions are crucial. Carbon capture, utilization, and storage (CCUS) is a key solution, capturing CO_2 from industrial processes or the atmosphere for use or storage, and is widely recognized as a key measure (Essien et al., 2025). The cement industry generates a significant amount of carbon dioxide emissions, with direct emissions accounting for 90% of total emissions. These emissions are primarily from the calcination process and fossil fuel combustion within the facility. Indirect emissions, which account for 10% of total emissions, originate from energy use and carbon dioxide decomposition, transportation, and ancillary services outside the plant (Klee et al., 2011). The energy needed to make Portland cement can vary between 3–6 MJ/kg of clinker, depending on the raw materials and the method utilised (Ige et al., 2022). CO_2 concentrations are expected to rise to approximately 800 parts per million unless significant changes are made in the economy, technology, and society (Huntzinger and Eatmon, 2009).

Therefore, the cement industry is a major industrial polluter of greenhouse gases (GHG), and lowering emissions in this sector might result in a considerable drop in GHG releases overall (Boesch and Hellweg, 2010). Climate change is a global issue causing rising temperatures, weather patterns, and severe natural disasters. Human activities, particularly fossil fuel combustion, release greenhouse gases like CO_2, methane, and N_2O into the atmosphere. Traditional energy sources contribute to most GHG emissions, highlighting the need for transitioning to cleaner alternatives. Mitigating greenhouse gas emissions is crucial to address climate change's impacts on ecosystems, economies, and human societies, including heat waves, droughts, storms, and sea-level rise (Owulade et al., 2025). By pinpointing resource impact hotspots, life cycle assessment (LCA) has recently been used to lessen environmental effects on the cement industry. Clinker production, the most important step in the making of cement, adds to air pollution and the use of fossil fuels (Gursel. et al., 2014). Methods such as resettling cement clinker ratios have been investigated to lower these emissions. Blended cements have gained more attention recently as a crucial tactic for the cement industry's decarbonization. Of these, CEM III has demonstrated a great deal of promise in lowering greenhouse gas emissions due to its high percentage of ground granulated blast furnace slag (GGBFS). When finely ground, GGBFS, an industrial by-product of the steel industry, can be used as an additional cementitious material to replace a significant amount of clinker. In addition to reducing CO_2 emissions, this swap promotes the circular economy. Several studies, including those by (Stafford et al., 2016), and (Ige and Olanrewaju, 2023). have shown that CEM III cement is a promising low-carbon substitute because it emits significantly less CO_2 than conventional types like CEM I. The use of new technologies and the consideration of waste as raw material and energy are being investigated. Many nations desire to replace their fuel supplies and raw materials through co-processing, which includes alternative fuel-raw materials (AFR) (Stafford et al., 2016). One of the most trustworthy methods for figuring out the percentage of environmental impact divided by cement production stages is LCA.

The goal of this study is to thoroughly evaluate the carbon footprint of the MENA region's present and future cement production. The research takes into account both direct and indirect emission sources throughout the cement manufacturing process by analyzing the environmental impact across different nations. The study aims to determine the most emission-intensive phases and highlight viable approaches for carbon reduction and enhanced sustainability in the industry through a mix of data analysis, emission factor evaluation, and cross-country comparisons. Accordingly, the main objectives of this study are:

1. Measuring the carbon footprint of cement production in selected countries in the Middle East and North Africa (MENA) region using life cycle assessment (LCA) methodologies.
2. Comparing emissions from different types of cement, with a particular focus on the benefits of using blended cement.
3. Analyze current and future production scenarios to determine the most carbon-intensive process in the production chain.
4. Exploring possible strategies that reduce the resulting emissions, resulting from replacing raw materials and adopting technology, with a focus on the Iraqi cement sector.

Assessment of the cement industry

LCA – this technique assesses the environmental impact of a product at every stage of its life cycle, including extraction, transportation, use, and disposal. It takes into account energy use, emissions, waste generation, and resource depletion. LCA offers an extensive, quantitative analysis to improve environmental sustainability in products and activities and make well-informed decisions (Barbhuiya and Das, 2023). In the cement industry, LCA is being utilized to lessen environmental effects, especially in the manufacturing of clinker. Because of air pollution and fossil fuel usage, this stage is critical. Resettling cement/clinker ratios, viewing waste as energy and raw material, and introducing new technologies like co-processing, which incorporates alternative fuel-raw material (AFR) are some strategies being investigated to lower these emissions. By using tires and other waste from other industries as energy in the cement industry rather than landfills, the process preserves natural resources (Kaygin, 2022).

According to LCA research, the synergistic products have positive environmental effects To lessen the negative environmental effects of cement, numerous life cycle assessment studies modeled various scenarios for fuel and raw material substitution (Strazza et al., 2011; Aranda Uson et al., 2012; García-Gusano et al., 2013). To determine the emissions and energy usage resulting from the production of cement, numerous studies have been carried out (Çankaya and Pekey, 2019). Design optimization relies heavily on LCA. It enables architects, engineers, and designers to make well-informed decisions by providing them with relevant information about how their decisions affect the environment. LCA improves construction projects' environmental performance by taking life cycle impacts into account (Evangelista et al., 2018). LCA supports legislation aimed at reducing the sector's environmental impact and promoting sustainability goals. Understanding the LCA makes it easier to pinpoint significant actions and materials released, and focusing on these procedures to reduce the main causes (ISO14040, 2006).

Strategies to reduce the environmental impact of the cement industry

Numerous studies have investigated ways to lessen the environmental impact of cement production, especially in the MENA region, using LCA methodologies. For example, Ali et al., (2016) conducted the first LCA-based analysis of the Egyptian cement industry, showing that coal usage in production contributes significantly to global warming and respiratory-related impacts. Similarly, Çankaya and Pekey (2019) in Turkey, demonstrated that the use of alternative fuels reduced clinker-related emissions by 12%, improving ecosystem quality and reducing climate impact. Biswas et al. (2017) highlighted the role of solar-powered electricity and recycled steel in reducing carbon emissions. Al-Nuaimi et al. (2019) emphasised how geopolitical disruptions can elevate transport-related emissions by over 70%. Beyond the MENA region, studies have explored materials and fuel-based alternatives. Hason et al. (2020) assessed the use of eco glass cullet cement (Eco-GC-1) cement, incorporating waste glass, which reduced energy use and CO_2 emissions by up to 20% compared to OPC (Georgiopoulou and Lyberatos, 2018). Further evaluated alternative fuels such as RDF and TDF, identifying RDF as the most environmentally favourable scenario. Additionally Li et al. (2016) investigated the integration of blast furnace slag (BFS) and found that although human toxicity slightly increased, the reductions in abiotic depletion (72%) and land use (41%) were significant. In the context of moving towards sustainable alternatives to reduce the carbon footprint of the cement industry, some local studies have shown the possibility of utilising industrial and household waste as effective partial alternatives. Ihsan et al. (2024a).The study showed. Replacing cement with sludge ash from water and wastewater in proportions of up to 15% improves the mechanical properties of concrete and reduces reliance on traditional clinker. Another study by Ihsan et al. (2024b) also showed that the use of 20% ground brick powder as a partial substitute for cement contributed to improving compressive strength, confirming the pozzolanic properties of this material and its potential role in enhancing the sustainability of concrete mixtures. Simultaneously, a lot of research has been done to improve the sustainable concrete mixtures' mechanical performance. Tobeia et al. 2021, and Mohammed et al. 2018, investigated how to reduce the need for virgin materials while increasing compressive strength by using recycled aggregates and polymeric materials. Golewski (2020) proved that quaternary binder systems with fly ash (FA), silica fume (SF), and nano-silica (NS) had better mechanical qualities and a lower OPC content, which indirectly resulted in fewer emissions. In a similar manner, Abdulkareem et al. (2020) utilizing recycled polystyrene, sustainable concrete was created that offers improved mechanical performance and lowers carbon emissions by reducing dependency on high-emission inputs. While mechanical upgrading using new materials may improve performance and environmental impact, the examined research reveals that using alternative fuels and supplementary cementitious materials (SCMs) can drastically reduce emissions.

Types of cement according to the study (based on EN 197-1:2011)

The European Standard categorises cements into five main groups based on their additives. The five main groups of cement types in American & European Standards are:

1. CEM I Portland cement – this is the most common type of cement and it mainly contains and some gypsum. It is characterized by high hardness and speed of hardening and is used in most general construction projects and up to 5% of minor additional constituents (such as: fly ash) consumes more energy and produces higher carbon emissions compared to other types due to the high reliance on clinker. Used in public construction projects such as roads, buildings, and bridges.
2. CEM II composite cement is made up of Portland cement, clinker, and other ingredients like(fly ash slag glass flour or stone cement) making it less environmentally impactful compared to ordinary Portland cement. There are several subtypes of CEM II based on additive components such as CEM II/A-V (which contains fly ash) and CEM II/B-S which contains slag and up to 35% of some other individual components used in general construction projects but preferred in projects that need less environmental impact.
3. CEM III sulfate-resistant cement (SRC) or high sulfate resistance cement – this type contains a large percentage of slag (about 35–65%) or percentages of blast furnace slag that may reach 95% giving it excellent resistance to sulfates and other chemicals used in environments exposed to the effects of high sulfates, such as coastal areas or in installations that require high corrosion resistance.
4. CEM IV – this species contains a large percentage of fly ash (approximately 15–55%) with clinker. This type is ideal for projects that require special environmental specifications, such as public projects with low environmental impact.
5. CEM V lightweight cement – composite cement consists of Portland cement and combinations of more than one additive, as it contains other additional components such as glass flour or limestone. Used in places where lightweight cement or additional heat resistance is required.

METHODOLOGY

The methodology includes LCA, predictive statistical modelling, and carbon footprint assessment of cement manufacturing in the MENA region. To forecast CO_2 emissions₂ until 2030, a linear regression model was created using cement production data from the National Mineral Information Centre, World Budget Reports (2023), official reports, and cement plant records. Life cycle analysis produced emission factors for each cement type using Brightway2 and the Consequential 38 database. By combining life cycle thinking with a long-term environmental vision, this integrated approach has made it possible to quantify current emissions and predict their potential for future reduction.

Experimental field work description

The Middle East and North Africa region was selected as the study area due to its strategic significance in the cement industry sector, as the region is experiencing a growing population and urban development, leading to increased demand for construction materials, especially cement. The countries included in this study are among the most active in this sector and are: Turkey, Iraq, Iran, Saudi Arabia, the United Arab Emirates, Yemen, Jordan, Egypt, Morocco, and Algeria. These countries were identified based on data availability, production level, and their regional impact on emissions from the cement industry.

The map in Figure 1. displays the geographical locations of the countries included in the study, and their borders within the regional framework of the Middle East and North Africa.

Emissions estimation and comparative study

In the framework of the assessment of the potential environmental impacts of the cement industry, a predictive approach based on trend analysis using a simple linear regression model was adopted, in order to estimate future emissions of CO_2 until 2030. This analysis was based on actual recorded emissions data during the period from 2000 to 2022, relying on official and reliable sources. The goal of this action was to build a clear understanding of the extent to which current patterns of emissions persist or change, which contributes to supporting future environmental policies and directing industry strategies towards more sustainable technologies.

CO_2 emissions determination for different types of cement using LCA

Carbon emissions from cement production were assessed using a LCA approach, implemented through the Brightway2 framework and its activity browser interface. Cement kinds

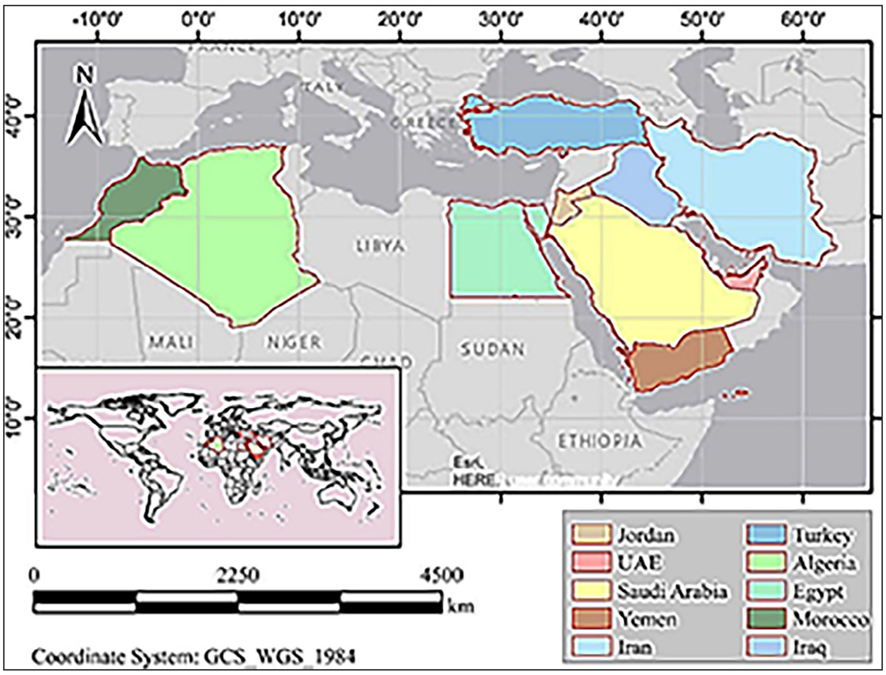

Figure 1. Map showing the countries included in the study within the Middle East and North Africa region

were chosen in accordance with EN 197-1:2011, a European standard, while emission factors were derived from the LCA simulations. These emission factors were then applied to national production data to estimate overall emissions. Additionally, different cement production configurations were analysed to evaluate how varying the proportions of cement types influences total emissions and to explore the potential for emission reductions.

System boundaries and functional unit

Clearly defining the goal and scope of the LCA study involves specifying the purpose of the assessment, the functional unit (i.e., per ton of cement produced), the system boundaries (which processes and inputs/outputs are included), and the timeframe of the analysis. In this study, the goal is to evaluate and compare the environmental impact of various cement types produced across North Africa and the Middle East. To achieve this, system boundaries were established, and a functional unit was selected. All significant stages of cement production, including the extraction of raw materials, manufacturing procedures, electricity consumption, plant operations, and transportation to and from the location, are included in the system boundaries. Due to methodological constraints, this study takes a cradle-to-gate approach, omitting the packing phase, cement use, waste treatment, and final disposal. The usage of raw materials, transportation, energy, fuel, and the clinkering process are the five primary stages of the complete production process for the sake of clarity.

The inventory analysis

All of the inputs (such as raw materials, energy, and water) and outputs (such as emissions and waste) related to every phase of cement manufacture, from the extraction of raw materials to the gate of the manufacturing facility were recorded. These data were sourced from reliable and representative databases specific to the cement production systems under study. Table 1 presents the input-output inventory data per 1 kg of cement, obtained from the Consequential38 database and relevant literature. Characterisation factors were applied to various environmental flows to quantify their relative impact within the selected impact categories. Each environmental flow was multiplied by its respective characterisation factor to convert it into a comparable category indicator value. The dataset is based on averaged data collected from multiple cement producers between 2018 and 2022. This study employed the Brightway2 LCA framework to model the product systems and life cycles of different cement types, facilitating a comprehensive assessment of the environmental impacts associated with each inventory element.

Impact category

The Global Warming Potential (GWP) linked to cement production mainly results from fossil fuel combustion and clinker manufacturing. The

Table 1. Life cycle inventory of cement production considered

Materials	Portland cement CEMI	Portland blend cement				
		CEMII	CEMII	CEMIII	CEMIV	CEMV
Cement factory (unit)	2.73E-11	5.36E-11	5.36E-11	2.73E-11	2.73E-11	5.36E-11
Clinker (kg)	0.904	0.3529972	0.4703	0.341187058	0.341187058	0.375
Gypsum (kg)	0.049	0.03176941	0.024194558	0.027161545	0.027161545	0.019013581
Fly ash (kg)	-	-	-	-	-	-
Limestone, crushed (kg)	0.047	-	-	0.015947895	0.015947895	0.2593
Ground granulated blast furnace slag (kg)	-	0.116666667	0.2525	-	-	0.101666667
Ethylene glycol (kg)	0.00022	0.00019	0.00055	0.000225	0.000225	0.00031
Electricity (kWh)	0.043	4.67217E-05	4.67217E-05	4.67217E-05	4.67217E-05	4.67217E-05
Steel, low-alloyed (kg)	0.00005	0.0000525	0.00011	0.000071	0.000071	0.00011
	Output					
Heat (MJ)	-	0.161318309	0.161318309	0.161318309	0.161318309	0.09742987
Cement product(kg)	1	1	1	1	1	1

Note: values were extracted from Brightway2 Activity Browser.

results aim to guide climate policy development and help decarbonization efforts in the MENA region's cement industry.

Emission differences between cement types based on clinker content

Cement types were classified according to BS EN 197-1:2011 as part of the life cycle assessment conducted using Brightway2 and the Activity Browser, with modelling based on the Consequential 3.8 database (Biosphere 3) and the IPCC 2021 GWP method (no L). This classification reflects differences in clinker content, which directly influence each type's emission intensity. The results reveal a clear direct connection between clinker content and emission levels. CEM I, with the highest clinker content, results in the greatest emissions, while CEM III and CEMV, composed of a diverse mix of supplementary cementitious materials (SCMs), produce the lowest carbon footprint. This reinforces the case for a strategic shift in the MENA region toward increased use of low-clinker cements as a practical and effective strategy to achieve long-term decarbonization goals by 2030.

RESULTS AND DISCUSSION

The study highlights methodological trends and key findings related to the carbon footprint of cement production in the MENA region. It provides context for the current life cycle assessment and establishes a foundation for understanding the emission profiles of various cement types and national scenarios.

Cement production in Iraq, North Africa and East Asia

Cement production data for 2022 in Iraq, compared to countries such as Turkey, Iran, Saudi Arabia, and Egypt, shows significant variation in production volume, with Turkey ranking first by more than 74 million tons annually. In comparison, Iraq's production is only 32.4 million tons. This disparity is due to differences in political stability, technological development, and investment in infrastructure. While East Asian and North African countries witnessed significant investments and industrial progress, the Iraqi cement industry remained dependent on traditional methods and was affected by ongoing political crises. The comparison included ten countries from the region with varying levels of production, as shown in Figure 2, to ensure a fair and comprehensive representation of regional reality.

Greenhouse gas emissions in Iraq from the cement industry with a focus on MENA countries until 2030

Greenhouse gases such as water vapour, CO_2 and methane are key factors in global warming, with CO_2 being one of the most prominent gases resulting from human activities, especially from the cement industry, which represents a major source of air pollution. This analysis was based on cement industry carbon emissions data from the 2023 global budget, and a simple linear regression model was used to analyse emissions data from 2000 to 2022 via Excel. The linear equation represents the relationship between year (X) and annual emissions (Y) as follows:

$$Y = B \times X + A \quad (1)$$

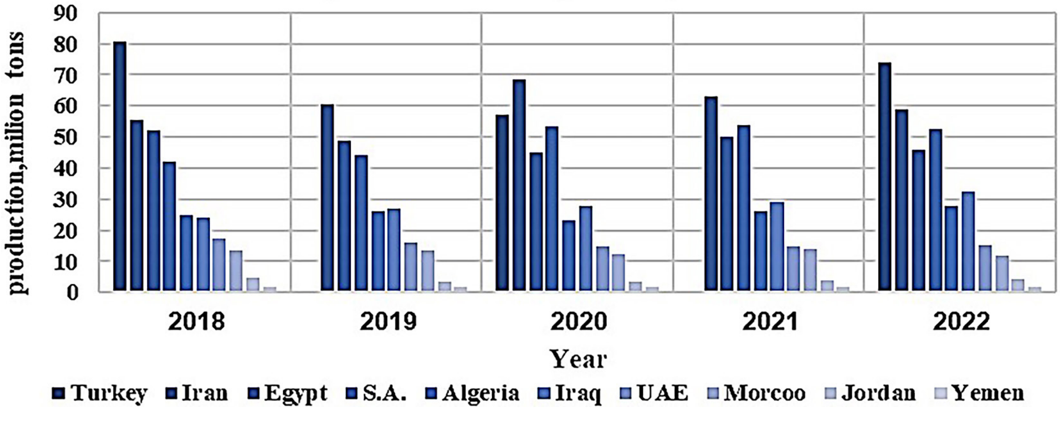

Figure 2. Cement production in the MENA region for the years 2018–2022

where: Y – represents the annual CO_2 emissions (in million tons), X – represents the year, B – is the slope of the regression line (indicating the emission factor per ton of cement), A – is the y-intercept, R^2 – (coefficient of determination) measures the strength and accuracy of the linear relationship.

The results indicate a strong positive relationship between time and emissions in most countries, with Turkey recording the highest R^2 value (0.93), as shown in Figure 3, reflecting high accuracy in future emissions forecasts, while countries such as Yemen and Jordan showed greater fluctuations in the data. The low P-values (close

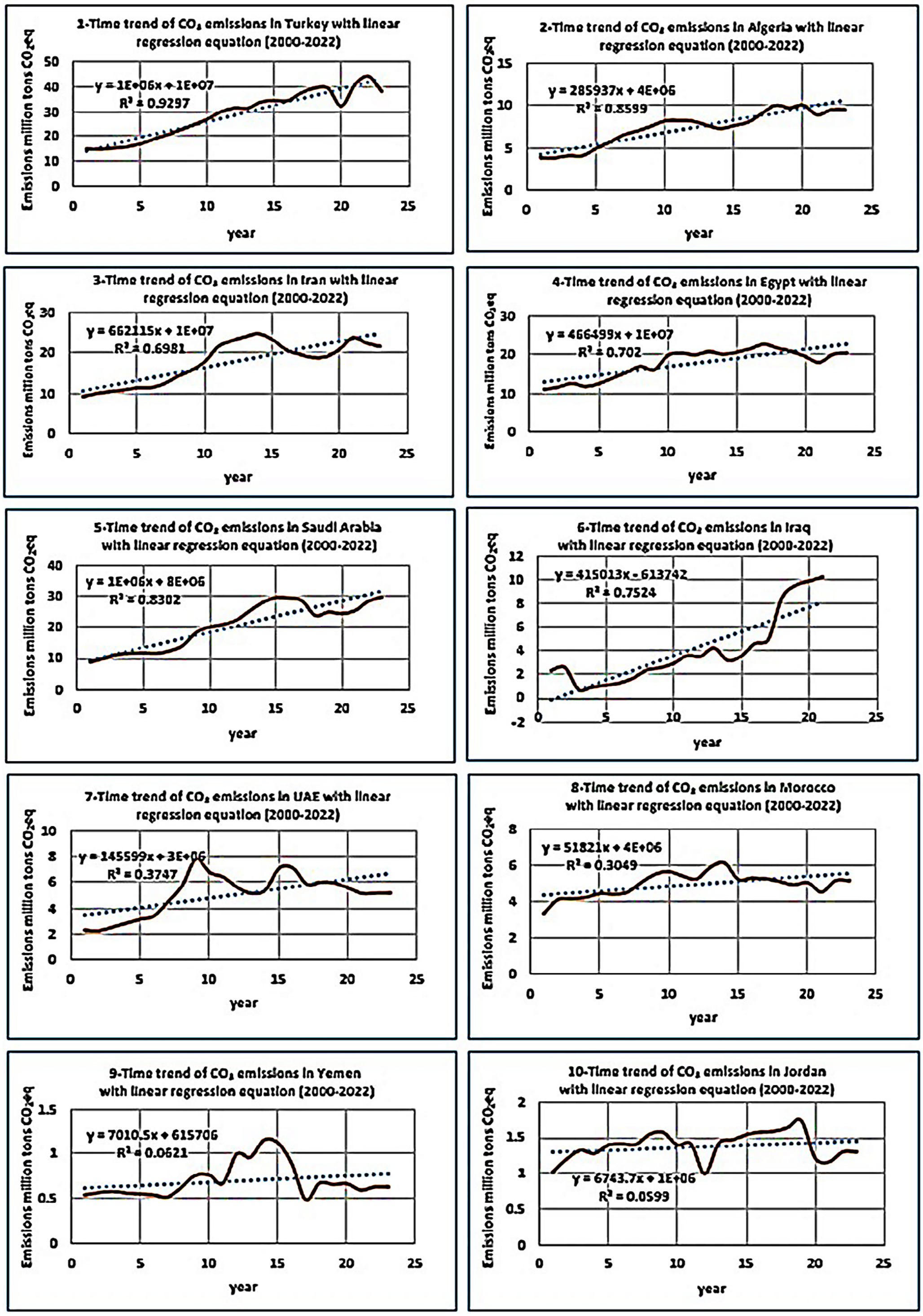

Figure 3. Time trend of CO_2 emissions in North African and Middle Eastern countries with linear regression equation (2000–2022)

to zero), as shown in Figure 4, indicate strong statistical significance, supporting the validity of the model and enhancing confidence in its application for environmental planning and climate policy in the region.

Emission factors per cement type

The calculated carbon emission factors and clinker content ratios for each type of cement are shown in Table 2. Using Brightway2 software and the Activity Browser interface, a life cycle evaluation was conducted to achieve these values. Using a conceptual framework based on Biosphere 3, the databases (consequential 38) were utilised to compute climatic impacts using the IPCC 2021 GWP 100 environmental assessment method. To ensure proper representation in terms of clinker composition and cement components, the cement types were further categorised according to the European standard EN 197-1:2011.

Applying life cycle analysis of cement production in the Middle East and North Africa region for the year 2022

Carbon dioxide emissions for 2022 were estimated for various MENA countries based on production volumes and the type of cement used, utilising emission coefficients for each cement type (CEM I to CEM V) derived from data documented within the LCA framework. The results revealed significant disparities among countries, with Turkey leading with emissions exceeding 65 million tons of CEM I, followed by Iran and Saudi Arabia. In contrast, Yemen and Jordan registered the lowest values due to lower production levels. Generally, higher emissions were linked to traditional cement types such as CEM I, while emissions dropped notably in blended cement types (CEM III to CEM V). Comparing these findings with global standards and emissions indicated that many countries' overall values align more closely with lower-emission variants like CEM III and CEM V, rather than CEM I. Particularly significant is Type(CEM III), which lowers the amount of clinker the main source of carbon dioxide emissions during production by containing a large percentage of secondary materials like GGBFS.

Consequently, increasing the production and use of CEM III presents a practical and sustainable strategy to cut future emissions, especially in the Middle East and North Africa (MENA) region and Iraq specifically, as this approach can help attain the Sustainable Development Goals and significantly lessen the environmental impact of the cement industry.

The results of this study align with previous research conducted by (Ige and Olanrewaju, 2023), which also confirmed that CEM III exhibits lower carbon emissions than CEM I, making it a promising alternative in sustainable cement production. Figure 5. clearly shows this trend by distributing emissions according to the type of cement in each country.

Table 2. Calculated carbon emission factors and clinker content ratios for each type

Cement type	Clinker content (%)	Emission factor (kg CO_2/ton cement)
CEM I	95–100	883
CEM II	65–79	578
CEM III	35–64	370
CEM IV	50–85	607
CEM V	50–69	318

Note: values were extracted from Bright 2 – activity browser based on the IPCC,2021 (noL).

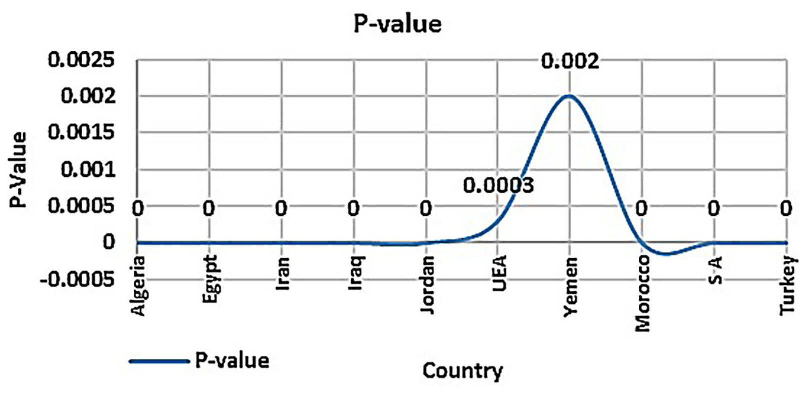

Figure 4. Comparison of p-values for cement emission trends across MENA countries

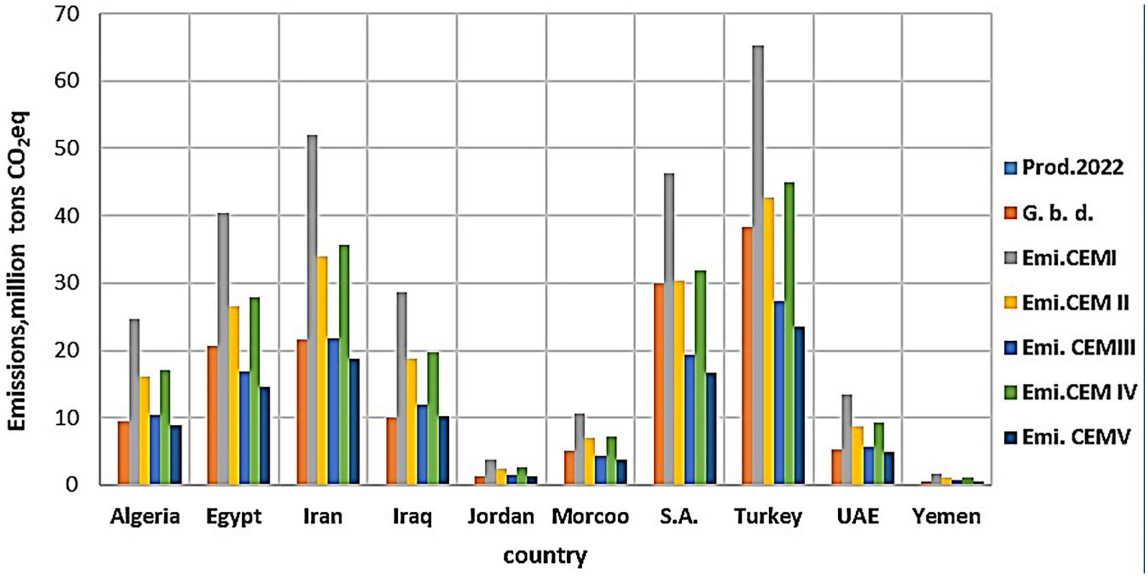

Figure 5. Total carbon dioxide emissions by type of cement produced in selected countries in the Middle East and North Africa region (2022)

Analysis of future carbon emission projections in the MENA region

Based on the emissions trends analysed in this study, projections from 2023 to 2030 suggest that overall emissions may continue to rise, driven by increased cement production in major countries such as Turkey, Saudi Arabia, and Iran. This suggests that although adopting low-carbon cement types can offset the benefits by expanding production, it underscores the need for more ambitious decarbonization strategies across the region. Figure 6 also shows projections of carbon dioxide emissions from the cement industry sector in the region, showing clear differences reflecting different levels of industrial production. In 2030, Turkey tops the list with (41 million tons CO_2eq), followed by Saudi Arabia (39 million tonsCO_2eq), then Iran (30.5 million tonsCO_2eq). Egypt, Algeria and Iraq come next with emissions ranging between 12 and 13 million tonsCO_2eq, while the UAE and Morocco record moderate emissions of less than 8 and 6 million tonsCO_2eq, respectively, as a result of improved production efficiency or the use of clean energy alternatives, and Jordan and Yemen come at the bottom of the list as a result of the decline in production volume. The data indicate relative stability in annual growth rates, reflecting the adoption of a linear model in forecasting and paving the way for the construction of more complex scenarios that take into account technological transformations and future environmental policies. Hence, the a need for integrated national strategies that work to achieve a balance between industrial growth and emissions reduction, especially in countries with the highest carbon emissions rates.

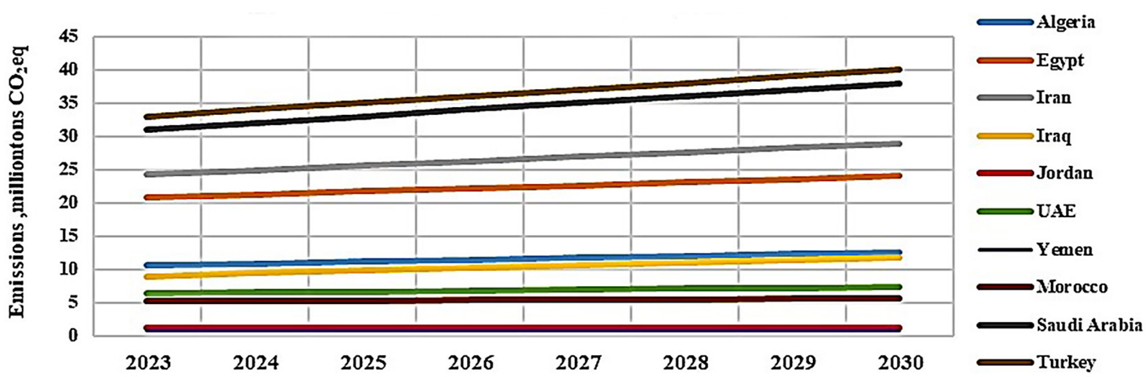

Figure 6. Annual projections of carbon dioxide emissions from the cement industry in countries of the Middle East and North Africa region (2023–2030)

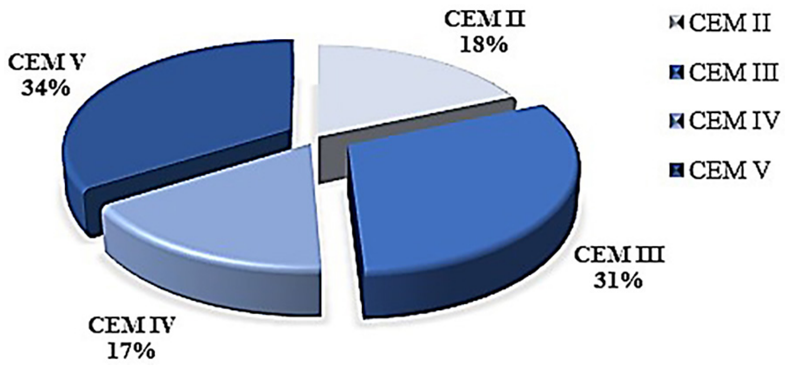

Figure 7. The reduction rates in CO_2 emissions compared to CEM I

Impact of clinker replacement with supplementary cementitious materials (SCMs) on carbon emissions reduction

One of the best ways to lower CO_2 emissions in the cement industry is to use Supplementary Cementitious Materials (SCMs) in place of clinker. Clinker, the key component in ordinary Portland cement (CEM I), is responsible for the majority of emissions due to the energy-intensive process of burning limestone at temperatures exceeding 1450 °C. In contrast, SCMs are typically processed at significantly lower temperatures (below 900 °C), leading to considerable reductions in both energy consumption and associated emissions. SCMs include a wide range of natural and industrial by-products with pozzolanic or cementitious properties, such as:

1. Fly ash generated from coal-fired power plants.
2. GGBS – sourced from the steel industry.
3. Natural pozzolana – volcanic ash and similar materials.
4. Other alternatives – such as crushed marble and plastic fibres.

These materials react chemically with calcium hydroxide in cement, enhancing the mechanical performance of concrete while significantly lowering clinker content. The practical implementation of clinker reduction is realised through the production of blended cements, classified into types such as CEM II, CEM III, CEM IV, and CEM V. Each type contains progressively higher amounts of SCMs and correspondingly less clinker.

As shown in Figure 7, the reduction rates in CO_2 emissions compared to CEM I are as follows: CEM II: 18% reduction, CEM III: 31% reduction, CEM IV: 17% reduction, CEM V: 34% reduction.

These findings are consistent with global literature, which affirms that increasing the proportion of SCMs in cement composition is a key pathway toward decarbonising the sector. The emissions reduction is quantified using the following formula:

$$Reduction\ ratio\% = \frac{Emi.CEM\ I - Emi.CEM\ X}{Emi.CEM\ I} \times 100 \quad (2)$$

where: *Emissions CEM I* = CO_2 emissions from traditional cement (100% clinker),
Emissions CEM X = CO_2 emissions from a given blended cement type.

CONCLUSIONS

Through a thorough combination of material developments, technological advancements, and energy strategies, this study identifies important prospects to lower carbon emissions in the cement industry in the MENA area. Blended cements, which contain supplementary cementitious materials (SCMs) like fly ash, slag, or natural pozzolans, are crucial, as demonstrated by the comparison of national emission patterns. These resources can Reduce the carbon footprint significantly by substituting some of the conventional ordinary portland cement (OPC). By using them, cement's most carbon-intensive component, clinker, is reduced, and industrial waste is recycled, promoting the ideas of the circular economy. However, material substitution alone is insufficient for deep decarbonization. Achieving significant emission reductions requires a holistic approach that combines multiple strategies, including:

1. Converting to alternative or low-carbon fuels like hydrogen, biomass, or refuse-derived fuels (RDF).
2. Enhancing energy efficiency through modern

equipment, advanced process control systems, and continuous monitoring technologies.
3. Reducing reliance on outside energy sources by recovering and recycling waste heat from kilns and other high-temperature activities to support plant operations or produce electricity.

These strategies must work together harmoniously. Integrated decarbonization routes can lead to noticeable, quantifiable, and long-lasting reductions in carbon emissions from cement manufacturing throughout the region; however, isolated efforts are unlikely to yield long-term outcomes. These results ultimately provide a solid basis for regional cooperation as well as the creation of national environmental policies, highlighting the necessity of multifaceted, coordinated efforts as opposed to depending solely on isolated or disjointed fixes.

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