The Role of Embodied Carbon in Sustainable Construction: A Review of Qatar's Practices and Perspectives

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Abstract

This study explores the urgent need for an embodied carbon (EC) assessment framework within Qatar's construction sector, driven by the country's rapid development and high carbon intensity in construction materials, such as cement and steel. Employing a systematic literature review through the Preferred Reporting Items for Systematic Reviews and Meta-Analyses(PRISMA) methodology and Visualization of Similarities (VOS) viewer for bibliometric analysis, this study identifies major gaps in Qatar-specific EC data and regulation. It highlights global best practices, particularly those from countries with mandated EC regulations, and discusses their potential adaptation to Qatar's unique environmental and economic context. This study advocates the establishment of a comprehensive EC database to inform construction practices aligned with Qatar's sustainability goals under its National Vision 2030. The findings suggest that a regionally adapted EC framework would significantly aid Qatar in reducing greenhouse gas emissions, given the country's heavy reliance on energy-intensive materials and its extreme climate. The study concludes with recommendations for the policy integration of EC assessments in Qatar's building sector, aiming to support sustainable urban development and climate resilience in the face of intensifying environmental challenges.

Key words: Embodied carbon, Qatar, construction sector, sustainability, climate change, National Vision 2030, environmental impact

Highlights

- There is a critical need for an embodied carbon assessment framework in Qatar's construction sector due to the carbon intensity of materials like cement and steel, which significantly contribute to greenhouse gas emissions.
- A systematic literature review and bibliometric analysis reveal significant gaps in Qatar-specific embodied carbon data and regulations, highlighting the necessity for a comprehensive embodied carbon database.
- Adapting global best practices from countries with mandated embodied carbon regulations is essential to address Qatar's unique context and challenges.
- The proposed regionally adapted embodied carbon framework aims to significantly reduce greenhouse gas emissions while considering Qatar's reliance on energy-intensive materials and its extreme climate.
- Recommendations include integrating embodied carbon assessments into Qatar's building sector policies to promote sustainable construction practices.

1. Introduction

The global construction industry is at a critical stage in the fight against climate change, accounting for nearly 40% of global carbon emissions annually and consuming 36% of the global energy [1]. Among these emissions, embodied carbon, representing the emissions from material manufacturing and construction processes, presents a particularly urgent challenge owing to its immediate and irreversible impact. Unlike operational carbon emissions which can be reduced over time through efficiency improvements or renewable energy adoption, embodied carbon creates an immediate "carbon spike" at the point of construction that cannot be retroactively mitigated [2] Recent studies indicate that embodied carbon will be responsible for half of the entire carbon footprint of new construction between now and 2050, consuming 25% of the remaining global carbon budget required to keep warming within 1.5°C [3]. Without immediate intervention, embodied carbon emissions from the construction sector alone could exceed 100 gigatons by 2060, potentially exhausting the entire carbon budget and maintaining a global temperature rise below 2°C [4].

The urgency of addressing embodied carbon is further heightened by its "lock-in" effect. Once materials are manufactured and buildings are constructed, these emissions are released irreversibly into the atmosphere. Embodied carbon studies is urgently needed because of its growing dominance in life-cycle emissions, representing over 50% of energy-efficient buildings, necessitating assessment and reduction to mitigate overall greenhouse gas emissions. [5] . This front-loading of emissions is particularly problematic given the The Intergovernmental Panel on Climate Change's (IPCC) warning that global emissions must peak by 2025 and reduce by 43% by 2030 to avoid catastrophic climate change [6].In response, countries like France and Sweden have implemented mandatory embodied carbon calculations for new buildings, while the Netherlands leads with its comprehensive National Environmental Database for lifecycle assessments, demonstrating that targeted policies can reduce embodied carbon intensity by up to 28.8% through strategic material selection and optimization.[7]

Qatar presents an urgent case for embodied carbon research, characterised by extraordinary economic growth alongside environmental metrics. As the world's third-largest holder of natural gas reserves and a leading LNG exporter, Qatar's GDP per capita ranks among the highest globally [8]. However, this prosperity has resulted in the highest per capita CO_2 emissions worldwide - approximately 102.6 million metric tons in 2022, equivalent to over 35 metric tons per person, compared to the global average of 4.7 metric tons per person [9]. The building sector in Qatar accounts for approximately 30% of the total final energy consumption, leading to considerable greenhouse gas emissions [10].

Qatar's construction sector is experiencing significant growth, with an impressive annual growth rate of 11.4%. This rapid expansion is primarily driven by the initiation of numerous megaprojects, which are transforming the landscape of the country. As these projects unfold, they not only contribute to the economy but also lead to increased carbon dioxide emissions, a concern highlighted in Figure 1. The interplay between construction growth and environmental impact underscores the need for sustainable practices in the sector. Therefore, while the construction boom presents opportunities for development, it also calls for a careful consideration of its ecological footprint]

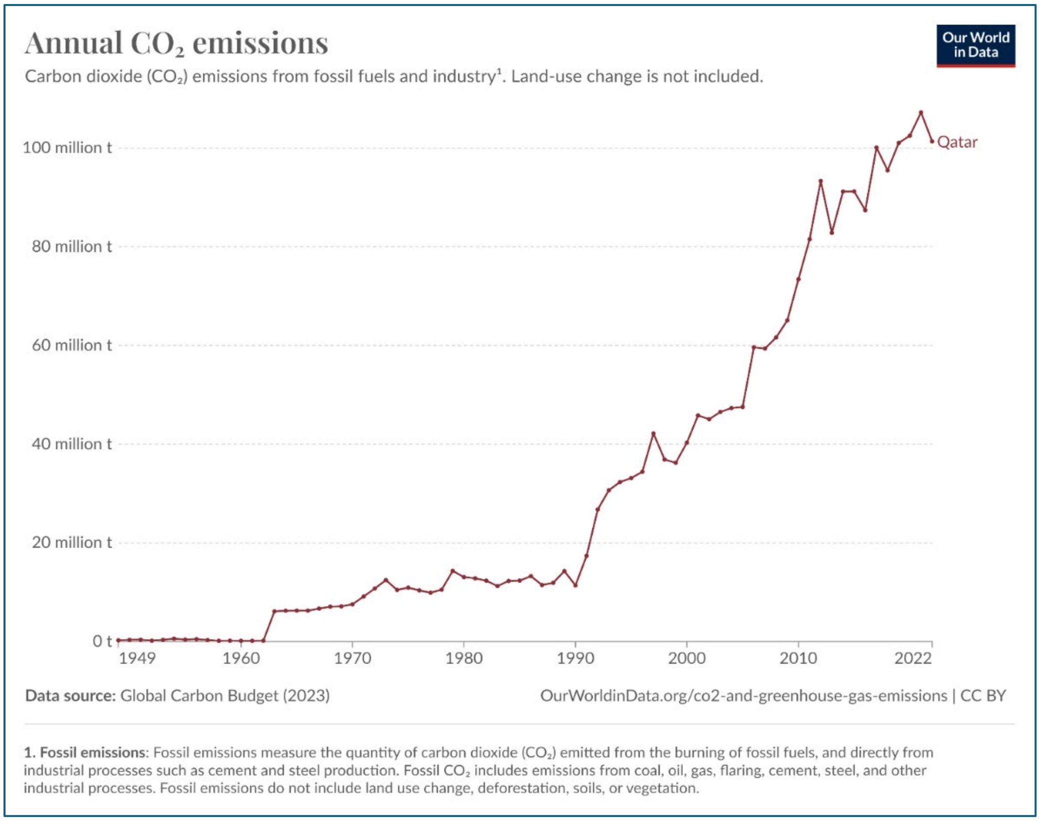

Figure 1Annual CO2 emissions in Qatar

Source: Global budget 2023, OurWorldData.org

The primary construction materials in this region are cement, concrete, and steel. The cement and construction industry contributes significantly to carbon emissions in Qatar, primarily because of the rapid growth of urbanisation and infrastructure development. However, this sector is responsible for considerable environmental impacts, notably in terms of global warming and embodied energy consumption. Qatar aims to construct a significant number of 'green' or carbon-neutral buildings across the Middle East and North Africa (MENA) region by 2030. Life cycle assessment (LCA) plays a pivotal role in supporting this goal by providing an objective and systematic approach for assessing the environmental impacts associated with construction materials and systems, thereby facilitating sustainable infrastructure design.[11] Cement production alone accounts for approximately 8% of global carbon emissions, and in Qatar, the increasing demand for cement driven by construction activities worsens this issue [12][13]. The reliance on Portland cement, a major component of concrete, further intensifies emissions, highlighting the need for alternative materials to mitigate the environmental impact [14]. Additionally, the energy-intensive nature of cement production, which relies heavily on fossil fuels, results in substantial carbon emissions [15]. This reliance on non-renewable energy sources underscores the importance of analysing energy consumption patterns to identify opportunities for efficiency and emission reduction. By adopting such sustainable practices, Qatar can reduce the environmental footprint of its burgeoning construction sector.

Qatar's vulnerability to climate change compounded the urgency to address these emissions. The Middle East is experiencing temperature increases twice the global average, with Qatar facing severe climate risks [16]. 1-meter sea level rise, expected by 2100, could affect 3% of Qatar's total land area, and a 3-meter rise could impact 8%. This could lead to a significant loss of coastal land, including valuable urban and industrial areas. [17]. Furthermore, Qatar's reliance on energy-intensive desalination for 99% of its water supply adds another layer of environmental stress, with desalination plants contributing significantly to the country's carbon footprint [18].

The country initiated several responses to these challenges. Qatar's updated Nationally Determined Contribution (NDC) aims for a 25% reduction in greenhouse gas emissions by 2030 compared with business-as-usual scenarios [19]. The implementation of the Global Sustainability Assessment System (GSAS) has resulted in certifying several buildings and potentially reducing carbon emissions [20]. The Qatar National Vision 2030 and the National Environment and Climate Change Strategy (NECCS) further demonstrate a country's commitment to environmental sustainability [19]. Qatar National Vision 2030 aims for sustainable development by addressing climate change while balancing economic growth and environmental stewardship. The nation targets a 25% reduction in greenhouse gas emissions by 2030 and plans to generate 20% of its electricity from renewable sources. Qatar is investing in renewable energy, carbon capture technologies, and sustainable infrastructure like green buildings and smart cities. These initiatives reflect Qatar's commitment to combat climate change and foster a sustainable future for its citizens. Such efforts not only aim to enhance the quality of life for residents but also position Qatar as a leader in environmental innovation and sustainability on the global stage. To further this commitment, the country is implementing carbon capture and storage technologies to reduce emissions from industrial activities, particularly in the oil and gas sector. In addition, Qatar is dedicated to developing sustainable infrastructure, including green buildings that meet international environmental standards and smart cities that utilize technology for efficient resource management. These points reflect Qatar's comprehensive approach to achieving sustainable development and addressing climate change while fostering economic growth and improving the quality of life for its citizens.[19]

However, a critical gap undermines these efforts, namely the absence of comprehensive data and studies on embodied carbon emissions in Qatar's construction sector. Although recent research in Doha City has revealed that residential villas and commercial buildings are significant emission hotspots, with some areas showing up to 40% higher emissions than city averages, no systematic assessment of embodied carbon exists [16]. Research has shown that the sector's carbon footprint is heightened because of its reliance on materials such as concrete and steel, whose production and transportation add considerable carbon emissions, especially under variable geopolitical conditions that impact material supply chains [21]. To address this, strategies such as the adoption of green building practices are becoming more prominent, aiming to reduce both embodied and operational carbon through energy-efficient design and sustainable construction materials [22]

This research gap is especially critical considering Qatar's ongoing infrastructure boom and the fact that studies in similar climatic regions have shown that embodied carbon can represent up to 50% of a building's total lifecycle emissions in hot climates, with concrete and steel contributing approximately 70% of these emissions [23]. While poor material choices could lock in decades of excessive emissions, informed decisions based on embodied carbon assessment could achieve immediate and permanent reductions of up to 30% in construction-related emissions [24].

This study aims to conduct a comprehensive literature review of embodied carbon research within Qatar's construction sector, focusing on three specific objectives: synthesising existing knowledge and methodologies related to embodied carbon assessment in Qatar's construction industry, with an emphasis on locally relevant factors such as material availability, construction practices, and climatic conditions; identifying key gaps and limitations in current research approaches, particularly in relation to the accuracy of carbon data for Qatar-specific materials and processes; and providing targeted recommendations for future research in Qatar's context, focusing on developing region-specific embodied carbon reduction strategies, optimizing the use of low-carbon materials and technologies, integrating embodied carbon assessment into regulatory frameworks, and addressing challenges posed by Qatar's unique environmental and economic landscape. The findings will contribute to Qatar's decarbonisation goals and support the development of sustainable construction practices in similarly resource-constrained and climate-challenged economies.

2. Research Methodology

To understand the environmental challenges and the need for embodied carbon studies in Qatar's construction sector, a comprehensive systematic literature review was conducted following the PRISMA framework. The review process involved searching academic databases such as Scopus, Web of Science, and Google Scholar for peer-reviewed journal articles, conference papers, and reports published in English between 2000 and 2023. The search focused on keywords related to Qatar OR "Gulf region") AND ("embodied carbon" OR "carbon footprint"), ("Construction sector" OR "building industry") AND (sustainability OR "environmental impact") BUT ALSO Qatar, ("Greenhouse gas emissions" OR "carbon dioxide") AND (construction OR buildings) BUT ALSO Qatar, ("Life cycle assessment" OR LCA) AND (buildings OR infrastructure) BUT ALSO Qatar,(Qatar OR Doha) AND ("sustainable construction" OR "green building"),("Environmental challenges" OR "ecological issues") AND ("construction industry" OR "built environment").

This methodological approach ensured a thorough examination of the relevant literature, thus providing a solid foundation for understanding the current state of research in this field. Following this, keyword analysis was performed using VOS viewer, a powerful tool for visualising and analysing keyword networks in research [25]. The viewer creates visual maps that help researchers identify emerging trends, hidden relationships between concepts, and influential keywords in a particular field. The customisable visualisation options of the software, such as adjusting the size, colour, and layout of the nodes, allow us to highlight specific aspects of the network. Furthermore, the VOS viewer provides quantitative metrics such as centrality and cluster analysis, which are valuable for identifying keywords and potential research gaps. This in-depth analysis of literature and keywords has contributed to a more comprehensive understanding of the environmental challenges and importance of embodied carbon studies in Qatar's construction sector [25]. Figure 2 shows the flowchart of the adopted methodology.

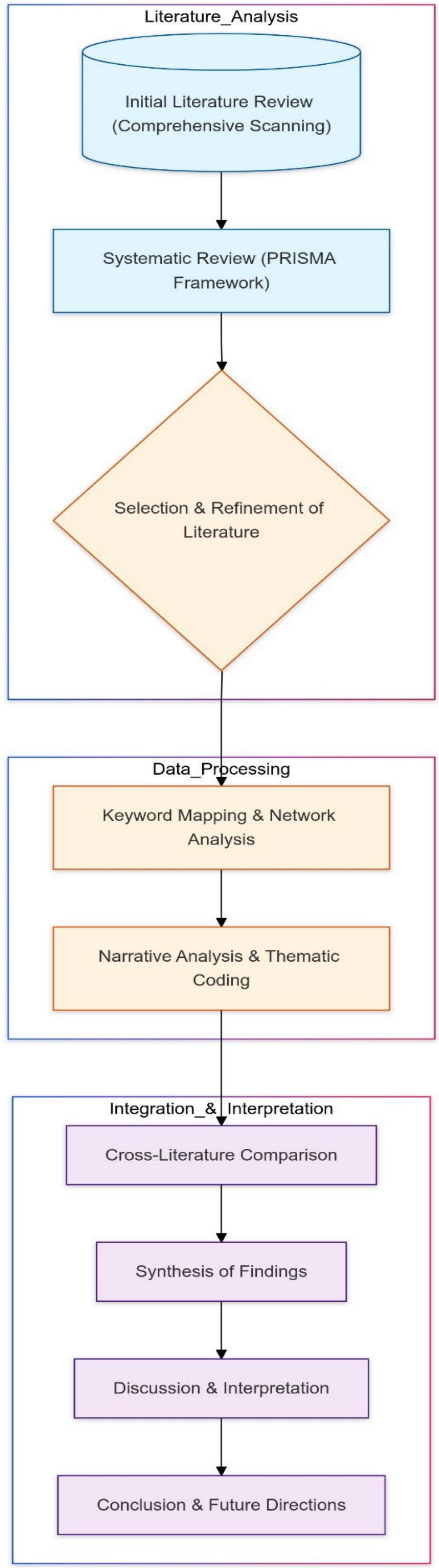

Figure 2: Methodology flowchart for the literature review.

2.1 PRISMA Flow Diagram

Building on the methodology described earlier, the study selection process was conducted systematically, and is illustrated in the PRISMA flow diagram in Figure 3. From the database searches, 255 records matched specified keywords. Of these, approximately 14 were removed as duplicate records, leaving 241 records for screening, based on their titles and abstracts. Of these, 87 were excluded for reasons such as irrelevant topics, lack of English language proficiency, lack of rigor, or insufficient detail. The remaining 154 reports were assessed for eligibility based on their full text. During this phase, 109 reports were excluded because they focused on operational carbon (36), insufficient data (13), methodological issues (12), and non-Qatari contexts (35), or were irrelevant to embodied carbon (13). Finally, 45 studies were included in the systematic review to form the basis for the subsequent analyses.

2.11 Study Selection Criteria

The primary focus was on studies that directly addressed embodied carbon in construction projects, particularly those that provided empirical data relevant to Qatar or similar contexts in the Middle East. Further studies are required to demonstrate robust methodological approaches to ensure reliability of the data and conclusions. Furthermore, only peer-reviewed articles were considered to ensure academic quality and credibility of the included studies. This scope includes studies that offer insights into embodied carbon accounting, reduction strategies, and relevant policy frameworks that affect the construction industry. Special consideration was given to research involving innovative materials, building techniques, and region-specific challenges, such as extreme climate conditions in Qatar and the Middle East.

The exclusion process was stringent. Studies that focused solely on operational carbon, which pertains to emissions from building operations rather than construction materials and processes, were excluded, because they were outside the scope of this study, which aims to concentrate on comprehensive analyses of embodied carbon and its impacts throughout the lifecycle of a building. This approach ensures that the research remains relevant and aligned with its primary objective of assessing the environmental implications of construction materials and methods. Additionally, studies were excluded if they lacked sufficient methodological rigor such as inadequate sample sizes or weak statistical analyses, which could have compromised the reliability of the findings. Non-English language publications were also excluded because of practical limitations of translation and interpretation within this review. Finally, studies that did not specifically focus on Qatar or relevant Middle Eastern contexts were excluded to maintain their geographical relevance. These studies focused on vastly different construction practices or regulatory environments that could not be directly compared to Qatar's unique challenges and opportunities regarding embodied carbon reduction. This rigorous inclusion and exclusion process ensured that only high-quality relevant studies formed the basis of the systematic review, providing a solid foundation for understanding the embodied carbon challenges and opportunities in Qatar's construction industry.

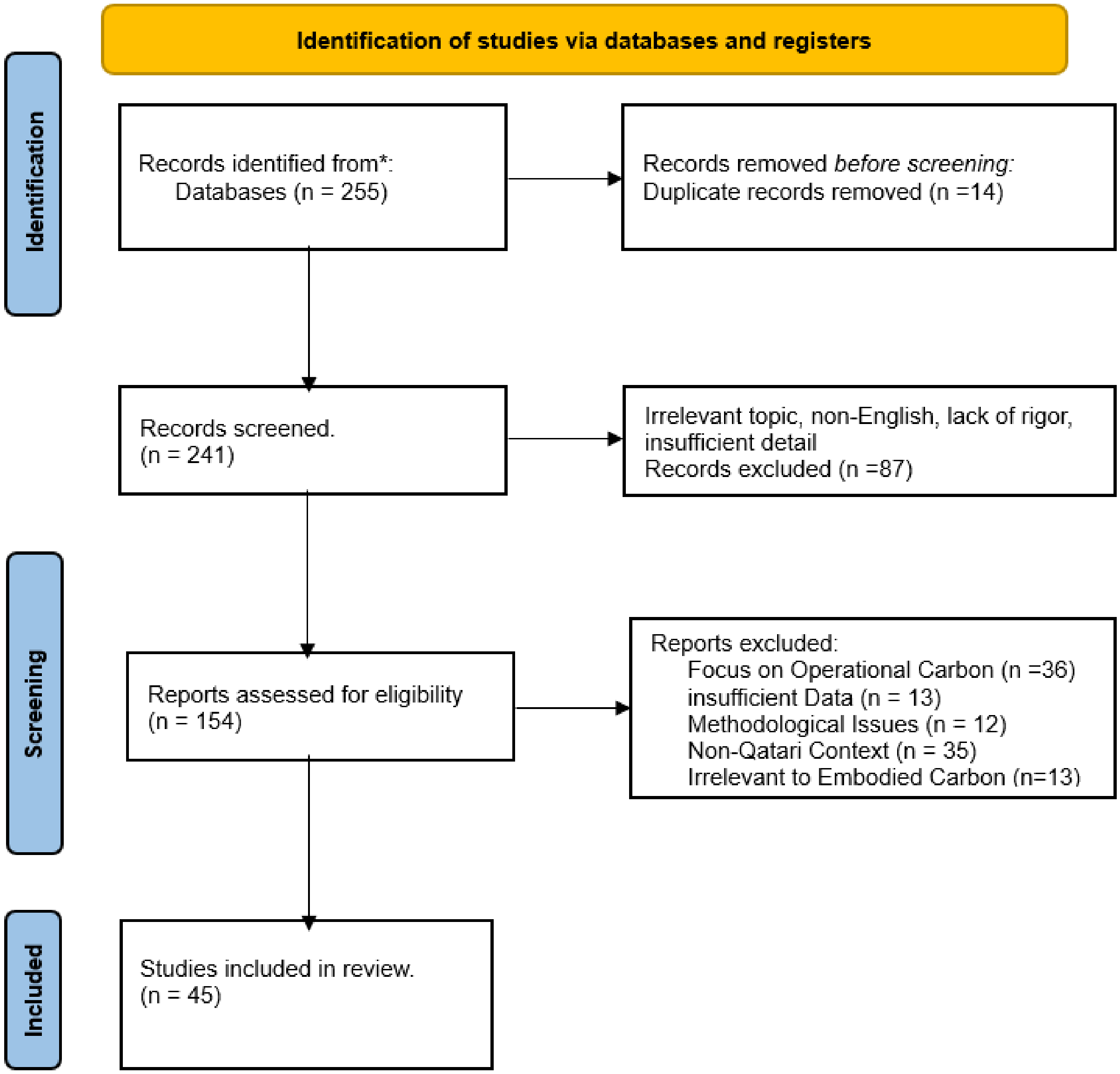

Figure 3: PRISMA flow diagram for review

The word cloud depicted in Figure 4 provides a visual representation of the most prominent topics covered by the selected journals based on an analysis of their titles. Word cloud visualisation offers a compelling snapshot of the thematic landscape prevalent in the titles of the selected journals. By analysing the frequency and prominence of specific words, this graphical representation highlights the key areas of focus and recurring subjects within the published literature. The varying word sizes in the cloud correspond to their relative importance or frequency of occurrence, allowing us to quickly grasp the dominant themes and research priorities in the field. The PRISMA flow diagram and word cloud visualisation are complementary tools that provide insights into the systematic review process and content of selected studies. The word cloud highlights the key terms from the included study titles, aligned with the focus areas identified in the PRISMA methodology. Prominence of terms like "embodied carbon" confirms effective screening for relevant studies. The absence of certain terms can validate exclusion criteria, such as the minimal presence of "operational carbon", thus supporting the exclusion of related studies. Geographic focus may be reflected by prominence of terms like "Qatar." The most prominent words indicated the main research themes of the included studies. The presence of method-related terms can reflect the methodological rigor emphasised in the selection criteria. Construction-related terms validate the industry focus. Connecting the word cloud to the PRISMA methodology allows researchers to validate their selection process, identify potential gaps or biases, and obtain a quick visual overview of the content and scope of the review.

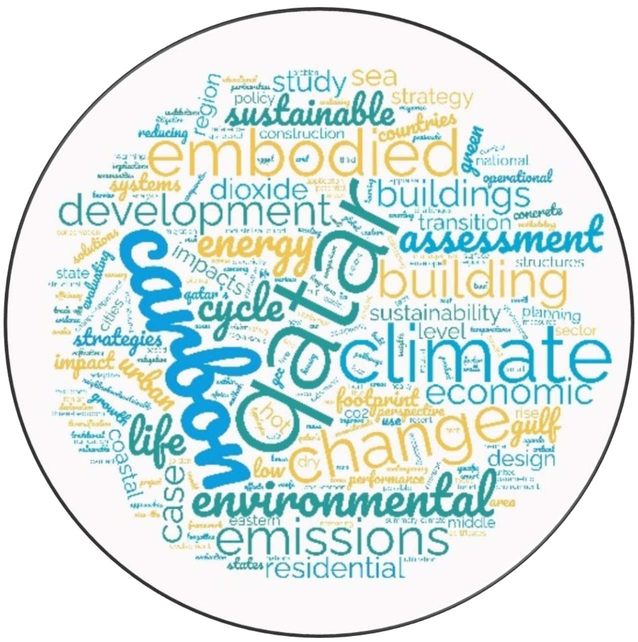

Figure 4: World cloud generated from titles

2.2 Keyword Network Analysis Using VOS Viewer

Keyword network analysis plays a crucial role in conducting comprehensive literature review. Mapping relationships between frequently co-occurring terms in the literature helps to visualise central themes and research clusters, such as the focus on materials such as carbon emissions, Qatar, life cycle assessments (LCA), and policy interventions [26]. This method not only highlights well-studied areas, but also exposes critical research gaps, such as the lack of focus on embodied carbon databases or localised material efficiency strategies relevant to Qatar's context. Moreover, by tracing the evolution of key terms over time, keyword network analysis offers insights into emerging trends and shifts in research focus, thus enabling a structured synthesis of the current state of knowledge [27]. Ultimately, this approach enhances the ability to identify overlooked areas and guides future research to address the specific needs of Qatar's construction industry to reduce embodied carbon emissions. To obtain a detailed understanding of the research landscape surrounding embodied carbon, sustainability, and climate change, a Qatar VOS viewer analysis was adopted. By visualising the connections between key terms, this analysis helps map out the areas of intense research activity and identify less-explored domains that could benefit from further study. For keyword network analysis, bibliographic data were gathered and organised using the EndNote software. The dataset includes a comprehensive collection of references related to embodied carbon, sustainability, and environmental challenges specific to Qatar. Each entry in the RIS file contained essential metadata such as author names, publication titles, journal names, keywords, and abstracts. This rich metadata was instrumental in conducting thorough keyword analysis. Before importing the RIS file into the VOS Viewer, the data were preprocessed to ensure accuracy and relevance. This step involves checking for duplicates, incomplete records, and inconsistencies in the dataset. Keywords were standardised to avoid variations in terminology (e.g., "CO2 emissions" vs. "carbon dioxide emissions"), which could potentially fragment the network visualisation. Additionally, a thesaurus file was prepared and applied within the VOS Viewer to further consolidate similar terms and ensure coherent analysis. Once the dataset was cleaned and ready, it was imported into the VOS Viewer. The software automatically extracted keyword data from the RIS file, which served as the basis for generating the co-occurrence matrix. This matrix forms the backbone of subsequent network visualisations, enabling the identification of key themes and their interconnections within the research literature. By leveraging the robust data management capabilities of EndNote and the analytical power of VOS Viewer, this approach ensures that keyword network analysis is both comprehensive and accurate, providing valuable insights into the research landscape of embodied carbon and sustainability in Qatar. Network analysis using the VOS Viewer to identify major research themes in embodied carbon and sustainability research in Qatar revealed five distinct clusters, which are explored in detail in the Results section. Figure 5 shows the keywords extracted by the VOS viewer for the analysis and the five different clusters formed. The research methodology involved using the VOS Viewer for keyword network analysis, explaining the cluster identification method and its significance in mapping the research landscape. In the results section, a detailed analysis of each cluster is presented, discussing the main keywords and their relationships, interpreting what each cluster represents in terms of research focus or themes, and discussing how these clusters relate to the research objectives and the broader field of embodied carbon and sustainability in Qatar. This discussion reflects on how these clusters align with or diverge from the existing literature and considers the implications of these thematic groupings for future research. When discussing the clusters, they are linked to relevant literature, and their significance within the context of the research aims is explained, helping to understand the importance of these clusters and their relevance to the study's objectives.

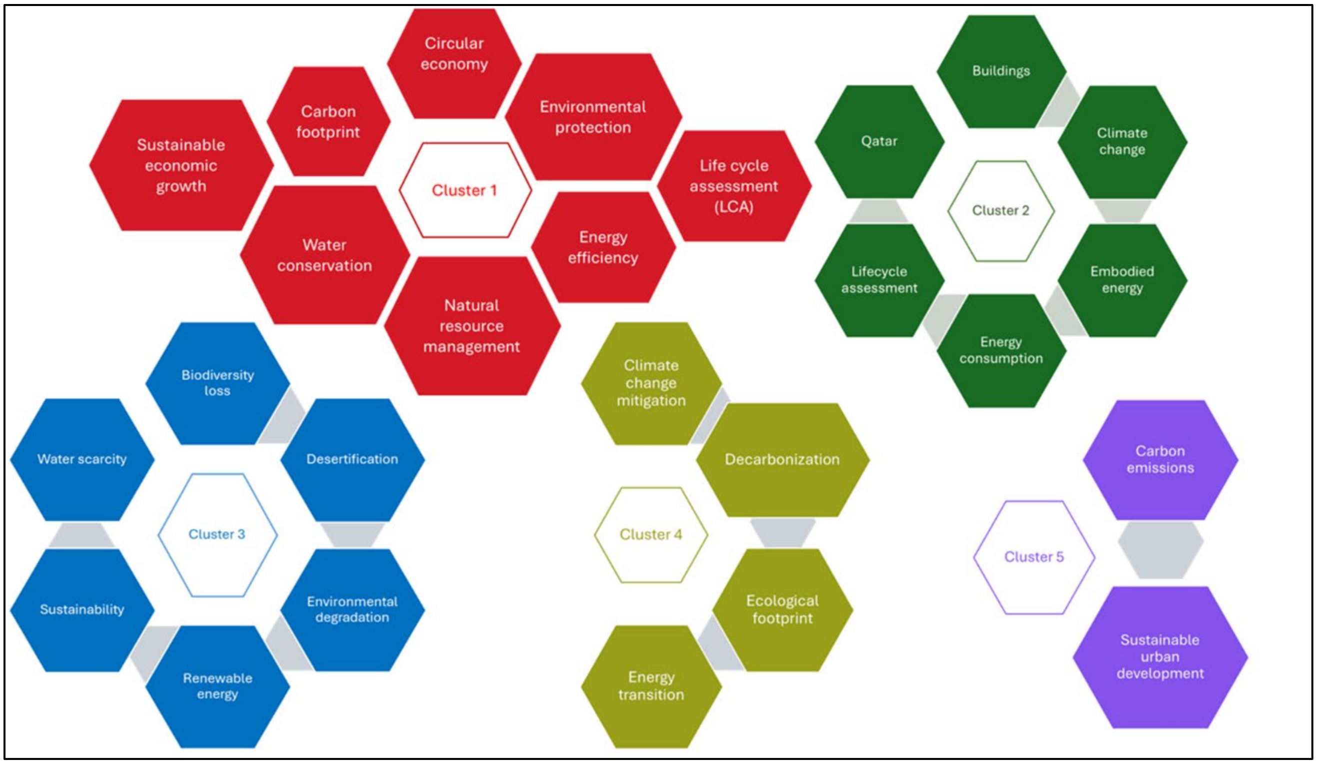

Figure 5: Clusters formed after key word analysis

2.3 Narrative Review

Narrative methodology is a qualitative approach that helps understand and interpret complex issues by focusing on the stories, patterns, and underlying themes within the data. It goes beyond simply summarising the findings by providing a deeper, more holistic view of the subject, allowing the researcher to connect individual data points into a broader, meaningful context. In this study, narrative analysis was used to synthesise the results from the systematic literature review and keyword network analysis, drawing connections between global decarbonisation trends and the specific challenges of Qatar's construction sector. This method allows tracing the evolution of embodied carbon research, identifying gaps in localised data, and highlighting the need for region-specific strategies. Integrating both global best practices and local notes narrative methodology offers a rich, comprehensive framework for understanding how Qatar can address embodied carbon in its built environment, ultimately supporting its sustainability goals.

3. Results and Discussion

VOS viewer provides outputs in three formats: overlay, density, and network visualisation. In this study, network visualisation was employed to find various keywords and their relationships, while overlay visualisation was used to track changes over time, based on the year of publication. Figure 6 and 7 show network visualisations of various keywords.

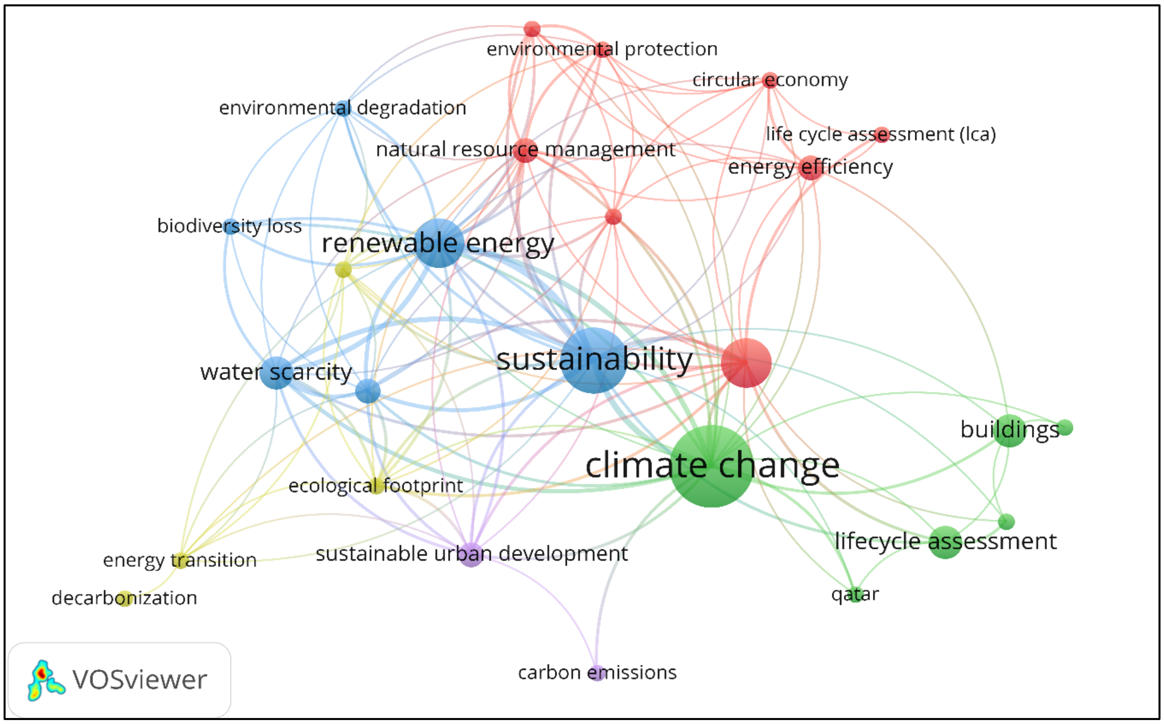

Figure 6: Network visualization of Key words

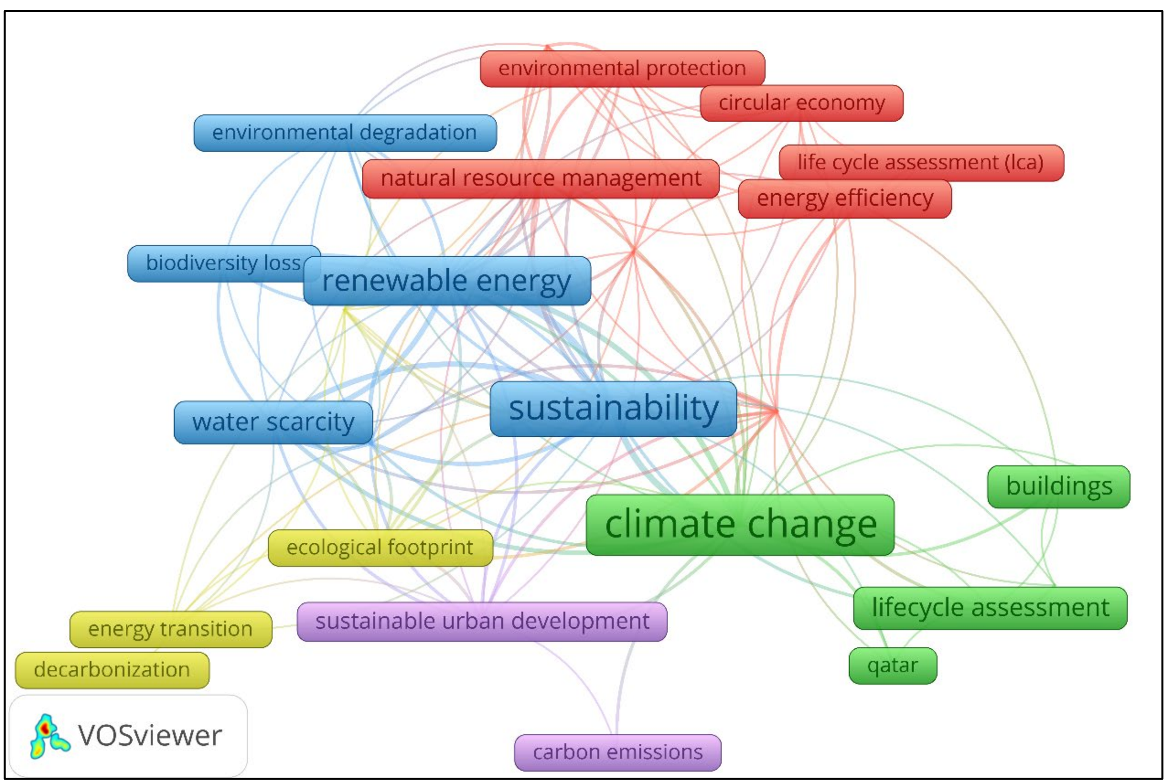

Figure 7 Network visualization highlighting key words

3.1 Keyword Analysis of Sustainable Development in Qatar: Five Key Clusters

Network visualisation revealed five main clusters of keywords related to sustainable development in Qatar. These clusters highlighted the interconnectedness of themes, such as resource use and carbon footprint, climate change and embodied energy in buildings, environmental challenges and renewable energy, decarbonisation and energy transitions, and sustainable urban development and carbon emissions. The analysis of these clusters, supported by evidence from existing studies, demonstrates the critical role of methods and databases in assessing embodied carbon in buildings and their impact on climate change. The red cluster groups or cluster 1 consist of terms related to carbon footprint, circular economy, energy efficiency, environmental protection, and life cycle assessment (LCA). These terms are highly interrelated and have strong connections with sustainable economic growth and natural-resource management. The strong network of relationships in this cluster suggests a focus on resource use, environmental impact assessments, and strategies for reducing carbon emissions within an economic growth framework. Further examination of the papers matches the findings of keyword analysis in detail. Cluster 2, The green cluster groups terms such as climate change, embodied energy, buildings, and life cycle assessment (LCA). This reflects the role of the building sector in climate change, embodied energy, and the LCA. The term Qatar is also connected, indicating a geographic focus or case study linked to regional climate issues.

Cluster 3, or blue clusters, focuses on renewable energy, environmental degradation, biodiversity loss, desertification, and water scarcity. These terms emphasise the challenges related to the environment and ecosystems and highlight the importance of renewable energy and sustainability efforts to address degradation and biodiversity concerns.

Cluster 4, the terms in this cluster include energy transitions, decarbonization, and ecological footprints. This cluster focuses on transitioning to cleaner energy sources and reducing carbon emissions, highlighting the broader concept of decarbonisation and its relation to sustainability efforts. This cluster includes climate change mitigation and sustainability. These terms appeared as central nodes and were connected to multiple clusters, suggesting their overarching importance across various sustainability topics. Finally, Cluster 5, which emphasises sustainable urban development and carbon emissions, underscores the importance of sustainable urban planning and development strategies to reduce carbon emissions and build resilient cities. A detailed analysis of the clusters is as follows:

3.2 Narrative Analysis and Interpretation

Building upon keyword network analysis, a narrative review was conducted to interpret the findings. The clusters were linked to the existing literature, and gaps were identified where Qatar's context was either underrepresented or entirely missing. For instance, while global studies highlight the role of low-carbon materials, few focus on how they can be adapted to Qatar's extreme climate conditions. The narrative review also highlights the need for a comprehensive embodied carbon database specifically tailored to Qatar's construction sector. This would align with global decarbonisation efforts but would require region-specific adjustments to account for material availability, climatic challenges, and the country's construction boom.

3.2.1 Energy Efficiency, Embodied Carbon, and Sustainable Construction Practices in the Middle East: Challenges and Opportunities

The rapid growth of the construction industry has contributed significantly to its carbon footprint and energy consumption. As part of its ambitious goal to develop sustainable or carbon-neutral buildings by 2030, it aims to improve energy efficiency and adopt green building practices. These efforts align with the country's broader strategy of supporting sustainable economic growth [28].

Alsabri and Al-Ghamdi [29] emphasised the importance of reducing the carbon footprint and improving energy efficiency, particularly in polymer production. They highlighted how circular economic principles such as recycling can mitigate the environmental impact of these materials. This is particularly relevant in the Middle East, where fossil fuel consumption remains high. Al-Naemi [30] reinforced this by stressing the need for energy efficiency and environmental protection in sustainable building practices. He advocated adapting global rating systems, such as Leadership in Energy and Environmental Design (LEED) and Green Star, to local circular economies and sustainable growth strategies, especially in hot and dry climates such as Qatar, where resource efficiency is crucial.

Al-Asmakh and Al-Awainati [31] further assessed the factors contributing to Qatar's carbon footprint. They concluded that a shift towards energy efficiency and adopting circular economy principles could better reflect Qatar's environmental protection efforts. This shift would also support sustainable economic growth by ensuring that emissions are closely aligned with domestic usage patterns.

Despite these efforts, the lack of energy-efficiency standards for buildings in the Middle East and North Africa (MENA) region has contributed to high CO2 emissions and environmental degradation. However, the adoption of nearly zero-energy buildings (nZEB) and energy-efficient designs can promote sustainable economic growth while reducing the carbon footprint of the building sector, according to Al-Saeed and Ahmed [32]. Qatar faces the challenge of balancing its economic growth by reducing its carbon footprint. Although per capita emissions are declining, further improvements in energy efficiency and adoption of sustainable practices remain necessary to achieve long-term environmental goals [33].

Andric et al.[34] highlighted that adopting green practices, such as green roofs and walls, offers significant potential for improving the energy efficiency and reducing the carbon footprint of buildings. These practices can decrease energy consumption by up to 42% and greenhouse gas emissions by 35%, thus contributing to environmental protection and alleviating the pressure on energy systems.

However, there is a notable gap in the research on embodied carbon in Qatar and, more broadly, across the Middle East. Few studies have been conducted in this field, including that by Al-Omari et al. [35], who used a Life Cycle Assessment (LCA) to evaluate buildings in Jordan. This study found that buildings contribute significantly to global greenhouse gas (GHG) emissions, with projections indicating a sharp increase in these emissions by 2030. Despite the environmental impacts of concrete structures, research on embodied carbon in Jordan and the Middle East remains limited. This underscores the need for further studies and standardised methodologies for assessing embodied carbon in the region. The effectiveness of LCA in quantifying CO2 emissions and its broader implications for sustainable construction are clear, as noted by Al-Omari et al [35].

A study conducted by Asif et al. in 2017 [36] on the LCA of a three-bedroom house in Saudi Arabia further highlighted the environmental and energy-related impacts of the rapid expansion of the Saudi construction sector. The heavy use of concrete and steel in construction has led to substantial environmental impacts, necessitating the adoption of more sustainable construction practices. Asif et al. [36] also emphasized the need for localized data and recommended further research into creating local databases on embodied energy for construction materials. They proposed the exploration of eco-friendly materials and construction methods to mitigate the environmental impacts. Moreover, expanding sustainability measures to include the operational phase and analysing life-cycle impacts across different climates has been proposed to enhance the long-term sustainability of the region.

The growing significance of embodied carbon is increasingly evident, as operational carbon is reduced through energy efficiency improvements. The study, "Life Cycle Building Impact of a Middle Eastern Residential Neighbourhood," highlights how embodied carbon, which includes material supply, production, transport, and construction, has become a critical part of the life-cycle impact of buildings in Kuwait. This study explored alternative construction methods for reducing embodied carbon, but noted that Kuwait's building codes currently lack provisions. Furthermore, the low energy costs in oil-rich countries such as Kuwait offer little incentive to reduce emissions. This study emphasises the need for region-specific building codes to address embodied carbon and improve sustainability. It also emphasises the importance of international standards, such as ISO 14044 and the ICE database, in guiding these changes [37].

Tarabieh and Khorshed [38] discussed the importance of reducing the embodied energy in buildings, particularly in Egypt, where hot and dry climates present specific challenges. They differentiated between embodied energy and carbon, noting that a higher embodied energy does not always result in a higher environmental impact, especially when renewable energy sources are used. However, a major challenge in this region is the lack of standardised methods for calculating embodied energy and carbon, leading to data discrepancies. This study calls for the development of region-specific tools such as local carbon coefficient databases and recommends exploring alternative low-carbon materials and creating guidelines for low-embodied-energy construction.

Qatar's Third National Development Strategy (2024–2030) underscores its commitment to sustainable economic growth, with a focus on reducing its carbon footprint, adopting circular economy principles, and improving energy efficiency [19]. The strategy aims to enhance environmental protection, foster long-term fiscal resilience, and stimulate innovation by committing to a 25% reduction in emissions, promoting renewable energy, and adopting advanced carbon capture technologies. Based on the discussions above, Figure 8 shows a bar chart that summarises how each country performs across the five sustainability metrics. The visualisation makes it easy to see Qatar's overall leadership in sustainability initiatives, Kuwait's generally lower performance across metrics, similar patterns between Jordan, Saudi Arabia, and Egypt, and the universally low availability of local carbon data across all countries.

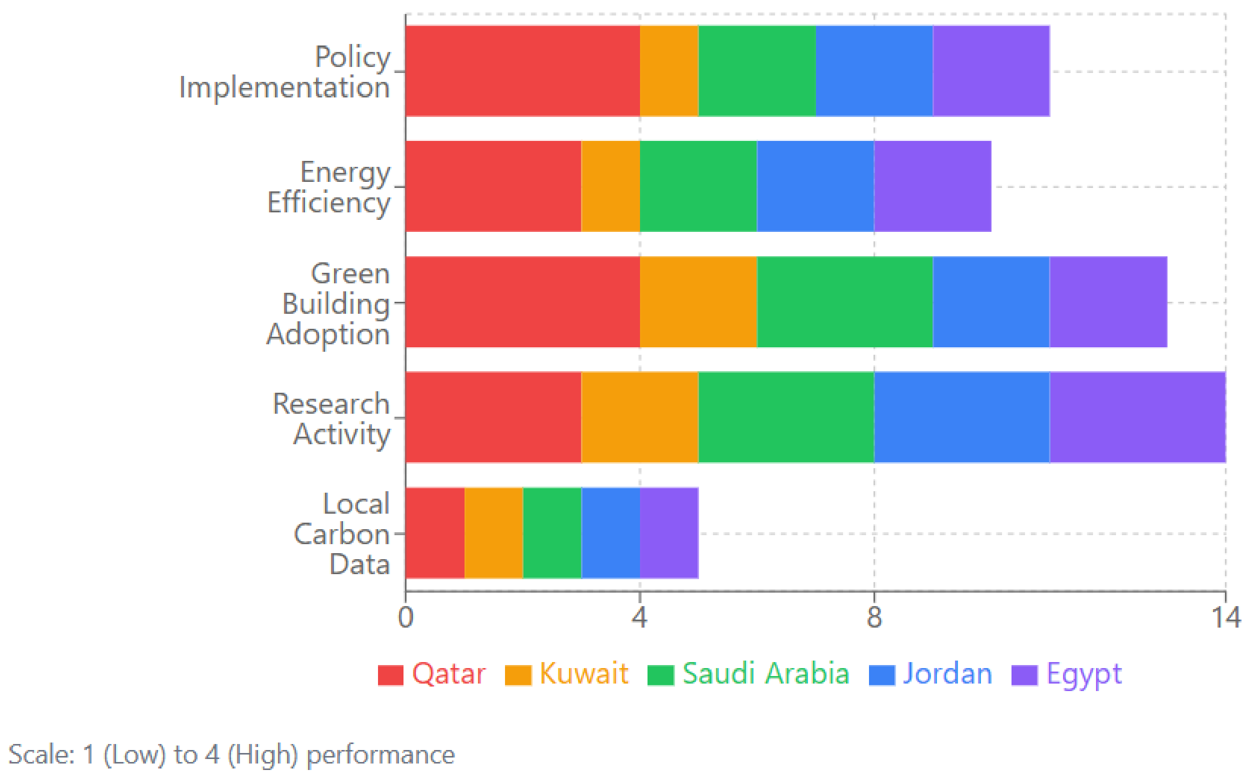

Figure 8 Middle East Sustainability Performance by Metric.

3.2.2 Life Cycle Assessment and Climate-Responsive Construction in the Middle East

The increasing urgency to address environmental challenges has placed a spotlight on the construction industry, particularly in regions like Qatar and the Gulf Cooperation Council (GCC). As the demand for infrastructure grows, so does the need for sustainable practices that minimize the environmental impact of building materials and methods. Life Cycle Assessment (LCA) has emerged as a crucial tool in evaluating the embodied energy and carbon emissions associated with construction, particularly in the context of concrete production, which is a significant contributor to embodied carbon. Recent studies conducted in Qatar have highlighted the potential for incorporating recycled materials and renewable energy sources, such as solar power, to mitigate these impacts. Furthermore, comparisons with traditional construction systems in neighbouring Iran have illustrated that embracing older methods can lead to substantial reductions in embodied carbon. As Qatar prepares for a projected increase in energy consumption due to rising temperatures, the integration of sustainable design and construction practices becomes imperative. This sets the stage for exploring the importance of LCA in the construction sector, the potential for innovative materials and methods, and the overarching goal of achieving sustainability in the face of environmental and economic challenges. A life cycle assessment (LCA) conducted in Qatar evaluated the embodied energy of buildings by assessing the environmental performance of precast and ready-mix concrete. Using local data, the study recommended the incorporation of recycled materials and solar energy to reduce the environmental impacts of concrete production, offering solutions applicable to Qatar and the wider Gulf region [40]. Similarly, research in Iran compared the embodied energy and carbon emissions of traditional and modern construction systems using ISO standards and the Inventory of Carbon and Energy (ICE) to demonstrate that traditional methods can significantly reduce embodied carbon, offering valuable insights into Qatar's context [41]. The integration of LCA into construction practices is essential because concrete contributes the largest share of embodied carbon. One of the primary challenges faced in Qatar is the reliance on global databases, such as the Inventory of Carbon and Energy (ICE). While these databases provide valuable information, they often lack the granularity and specificity needed for accurate assessments in the Qatari context. The environmental conditions, energy sources, and socio-economic factors in Qatar can be markedly different from those in other regions represented in global databases. For instance, Qatar's energy mix, which is heavily reliant on natural gas, may not be adequately reflected in global datasets that include a broader range of energy sources.Developing local databases and exploring alternative materials such as cement replacements could lower embodied carbon and improve sustainability in the GCC region [36]. A study examining embodied energy and emissions across the lifecycle of buildings emphasised that the operational phase tends to dominate emissions, reinforcing the importance of sustainable design and construction methods to reduce the overall environmental impact of residential buildings [35]. In Qatar, buildings are projected to experience a 30% increase in energy consumption for cooling by 2080, owing to rising temperatures. Without climate change mitigation, this increase will worsen the carbon footprint and strain fossil fuel-based energy systems, making it essential for Qatar to adopt sustainable building practices to manage environmental and economic challenges [34]. Sustainable construction efforts, such as the use of recycled materials in stadiums and green infrastructure during Qatar's FIFA World Cup 2022™, align with the nation's goal of hosting a carbon-neutral event while addressing broader regional environmental challenges [28].

Despite these initiatives, Qatar faces a trade-off between economic growth and climate change mitigation. The country's energy consumption remains high, but by embracing renewable energy and committing to its 2030 emission reduction targets, Qatar aims to decouple economic development from rising CO_2 emissions and align it with global climate agreements [33]. Current carbon accounting methods overestimate Qatar's emissions because of its role as an energy exporter. A more accurate system that focuses on domestic energy use would provide a clearer picture of the country's emissions and help align policies with sustainability goals [31].

Studies outside of Qatar echo similar concerns regarding embodied energy and carbon. In Egypt, research highlights the need for localised emission factors and low-carbon building designs, as global tools such as the ICE database may not accurately reflect regional conditions. This study calls for region-specific data and guidelines to enhance construction sustainability [38]. Similarly, in Saudi Arabia, an LCA of residential buildings stressed the impact of concrete on global warming potential (GWP), the need for sustainable materials, and improved energy management [42].

Lifecycle assessments (LCA) are essential for evaluating embodied energy and emissions across buildings in the Middle East. The use of alternative materials, cement replacements, and sustainable design strategies can significantly reduce embodied carbon, supporting environmental sustainability in rapidly developing Gulf nations, such as Qatar [43]. By adopting low-carbon structural designs, the embodied carbon in buildings can be reduced from typical emissions of 200-550 $kgCO_2e/m^2$ to as low as 30 $kgCO_2e/m^2$, underscoring the importance of a low-carbon approach for mitigating the environmental impacts of the built environment [43]. Qatar's national strategy further addresses climate change by focusing on reducing emissions in key sectors, such as buildings, energy consumption, oil and gas, and transportation. By integrating energy-efficient technologies and protecting 30% of its land and sea areas, Qatar aligns its development goals with global climate commitments [44].

The above findings are shown in a network diagram Figure 9, which illustrates the complex ecosystem of sustainable construction in Qatar and highlights key stakeholders, tools, impacts, and initiatives. At its core, Qatar serves as the central stakeholder (shown in purple), working in conjunction with the broader GCC Region and the Construction Industry to implement sustainable practices. These stakeholders are interconnected through various initiatives and assessment mechanisms, thereby creating a comprehensive approach to sustainable development. The assessment framework (depicted in orange) comprises three essential tools: Life Cycle Assessment (LCA), which evaluates the environmental impact throughout a building's lifecycle; the Qatar-specific Qatar Sustainability Assessment System (QSAS) Rating System; the Abu Dhabi's sustainability initiative ESTIDAMA framework, which provides sustainability guidelines for the UAE and can inspire regional efforts; and the ICE Database, which provides international standards for embodied carbon calculations. These tools form the foundation for measuring and implementing sustainability practices in the construction sector. Environmental impacts (shown in red) represent the critical challenges facing the region. These include increasing energy consumption, particularly in cooling requirements, rising carbon emissions from construction and operational phases, and the broader implications of climate change. These environmental concerns act as the primary drivers of policy development and technological innovation in the construction sector.

The diagram also highlights the major initiatives (green) that emerged in response to these challenges. These include the implementation of sustainable materials, such as recycled materials and cement alternatives, integration of renewable energy sources, and development of climate-responsive design strategies. These initiatives are directly influenced by both assessment tools and environmental impact, creating a feedback loop for continuous improvement. Policy elements (shown in blue) play a crucial role in guiding the overall direction of sustainable construction. Qatar Vision 2030 serves as the overarching framework, while specific projects, such as the FIFA World Cup 2022, have acted as catalysts for implementing sustainable practices. These policies are intrinsically linked to broader sustainability goals, including targets for environmental protection and sustainable development. The network demonstrates several key relationships, particularly how assessment tools inform solution implementation and how environmental impacts drive policy development. Notable interactions include the bidirectional relationship between sustainability goals and Vision 2030 and the direct influence of assessment tools on material selection and energy management. Climate change has emerged as a central driver influencing both policy decisions and technical solutions across the network. This interconnected approach ensures that Qatar's sustainable construction practices are comprehensive, measurable, and aligned with national and international environmental objectives. By fostering collaboration among stakeholders, this strategy not only enhances resource efficiency but also promotes innovation in sustainable technologies, ultimately leading to a more resilient built environment.

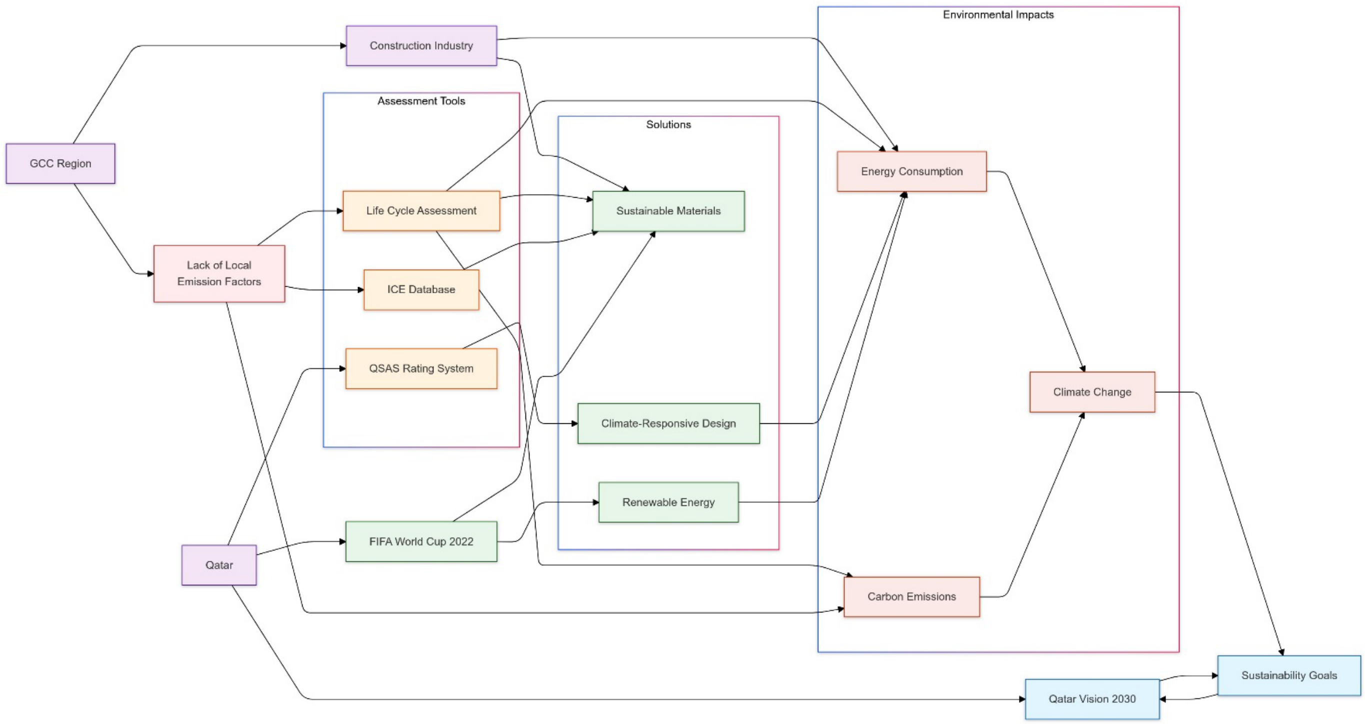

Figure 9 Network diagram showing the ecosystem of Qatar

3.2.3 Addressing Climate Change: The Urgent Need for Adaptation in Qatar's Coastal Areas

Global sea level rise driven by climate change poses a significant threat to the Arab region, with Qatar being one of the most vulnerable countries. Owing to its low-lying coastal areas and concentration of major cities along the coast, Qatar faces a heightened risk of flooding, saltwater intrusion, and coastal erosion, which could have devastating consequences for critical infrastructure and biodiversity. A projected 1-meter sea level rise could impact up to 3% of Qatar's land area, underscoring the urgent need for proactive adaptation measures. Early warning systems, strategic environmental assessments, and institutional monitoring are crucial for mitigating these risks and protecting Qatar's coastal environment [45].

The potential consequences of sea level rise in the Arabian Gulf, particularly in low-lying coastal areas, further highlight the vulnerability of coastal development in some countries and the need for coastal protection measures [46]. The study revealed a significant warming trend in Qatar's coastal region over the past three decades, which is consistent with global climate change patterns. This warming, particularly intensified in Doha and neighbouring cities such as Abu Dhabi and Ras Al-Khaimah during both the wet and dry seasons, underscores the environmental degradation occurring in the region [27].This environmental degradation is compounded by the lack of observational data on the eastern Arabian Peninsula, highlighting the critical need for further research to understand the full extent of climate change impacts and the effects of urbanisation and local pollution on extreme temperatures [27]. The above findings are shown as a mind map in Figure 10 for better visualisation and to identify the gaps and risks.

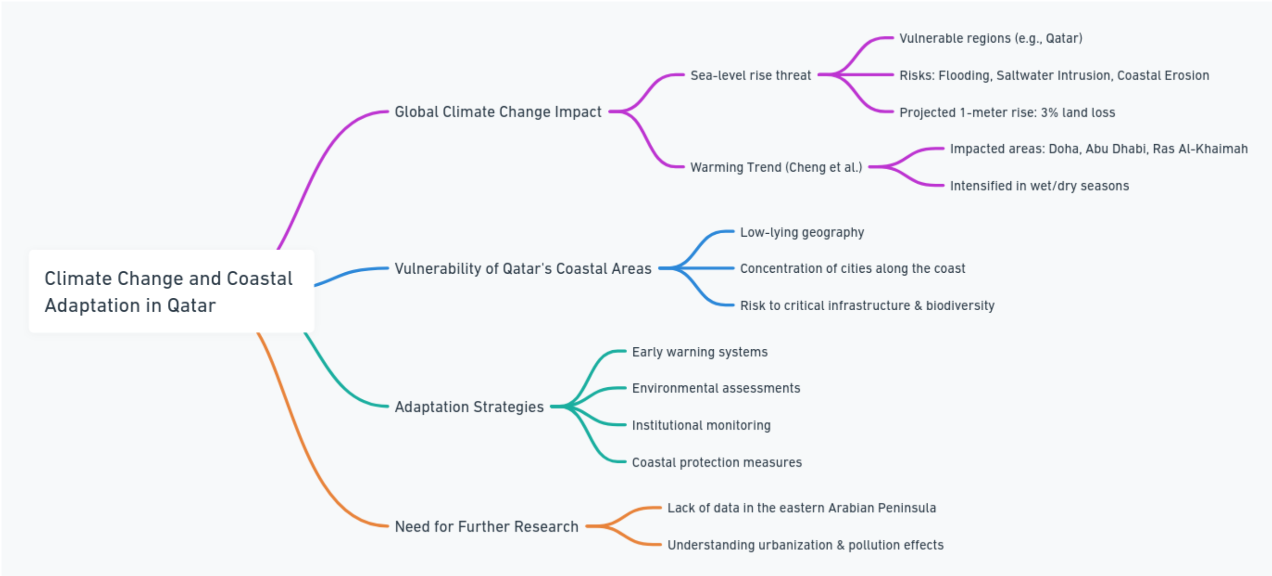

Figure 8 Climate change and coastal adaption in Qatar

3.2.4 Energy Transition and Climate Change Mitigation in Qatar: Challenges and Strategies

Qatar's rapid economic growth, fuelled by its hydrocarbon resources, has led to significant environmental challenges, including greenhouse gas emissions. As a signatory to the Paris Agreement, Qatar has committed to reducing its emissions. Carbon dioxide capture and utilisation (CCU) technologies offer a promising solution for mitigating these emissions. By capturing and storing CO2, Qatar can reduce its environmental impact and contribute to global efforts to combat climate change [47. Implementation of large-scale renovation of existing buildings and the integration of renewable energy systems to address the environmental impacts of climate change and ensure a resilient future for Qatar's residential sector was emphasised by Andric and Al-Ghamdi [34].

In addition to building regulations, Qatar has made strides to reduce gas flaring, a major source of emissions. For example, the Al-Shaheen oil field gas recovery and utilisation project successfully reduced the flaring by 80%. Continued efforts towards zero flaring and further advancements in sustainable energy practices are essential for Qatar to effectively address climate change and transition towards a more sustainable future [48].

Qatar's rapid urbanisation and reliance on coastal infrastructure further amplify its vulnerability to climate change. To address these challenges effectively, Qatar must prioritise climate-change mitigation strategies. By implementing sustainable urban planning, investing in coastal protection measures, and promoting climate-resilient development, Qatar can reduce its vulnerability to sea-level rise and other climate-related impacts, ensuring a more sustainable future for its coastal communities [45]. To address these challenges, Qatar needs to implement sustainable urban planning and development strategies. These include reforming urban planning practices, improving public transportation, and undertaking large-scale building renovations to reduce emissions and enhance resilience. By prioritising these measures, Qatar can mitigate the impacts of climate change and ensure a more sustainable future for its urban (environment). This study focuses on the challenges faced by small and vulnerable coastal areas (SVCAs) such as Qatar, owing to climate change. This highlights the urgency of adaptation strategies to address the impacts of rising temperatures, sea-level rise, and extreme weather events. This study acknowledges Qatar's national commitment to reducing greenhouse gas emissions and its efforts towards renewable energy sources. However, it emphasises the need for a comprehensive adaptation plan that considers Qatar's specific geographic, climatic, social, and economic conditions [49].

To effectively address these environmental challenges and ensure the resilience of a region's socioeconomic infrastructure, it is crucial to conduct comprehensive research and develop proper mitigation strategies. By understanding the intricate relationship between climate change, urbanisation, and local pollution, Qatar can take steps to mitigate the adverse effects of rising temperatures and build a more sustainable future [27].

Low-Emission Development Strategies (LEDS) play a vital role in mitigating climate change by providing a comprehensive approach to reducing greenhouse gas emissions. Decarbonisation, energy efficiency, and the transition to cleaner energy sources are key components of LEDS. By implementing these strategies, Qatar can contribute to global efforts to combat climate change and ensure a sustainable future for its population and economy [50]. Figure 11 shows a summary of Qatar's energy transition and climate change mitigation.

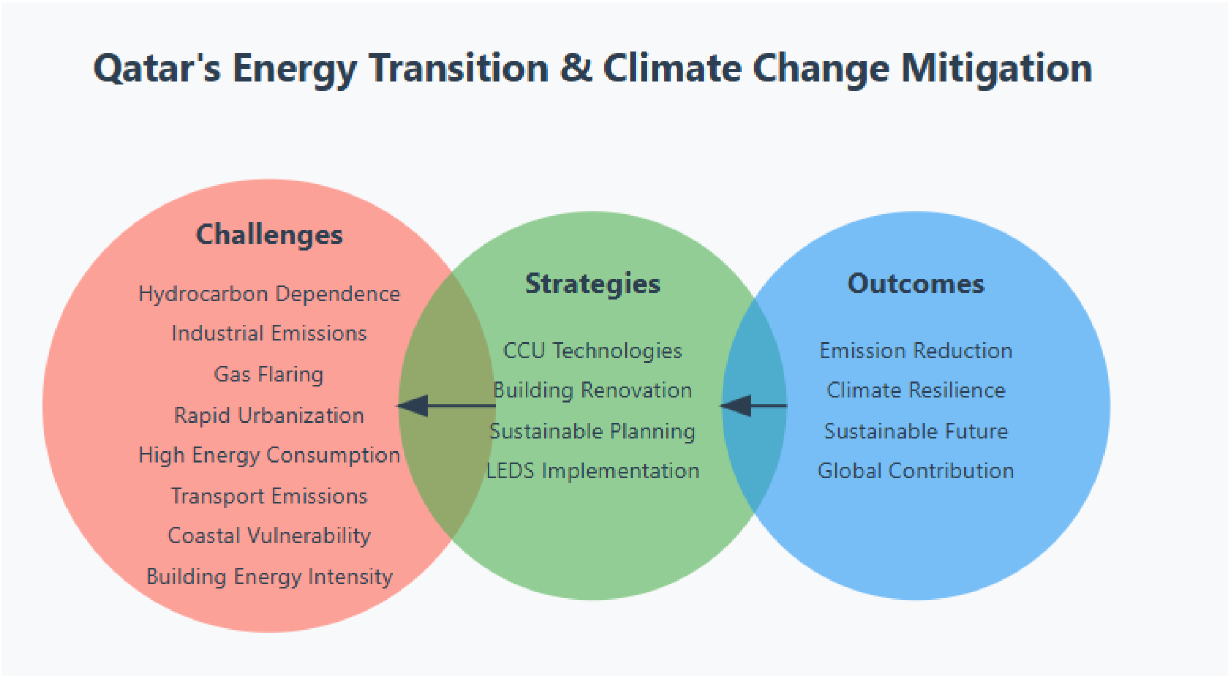

Figure 9 Summary of Energy transition and climate change mitigation in Qatar

3.2.5 Sustainable Urban Development and Carbon Capture: A Path Forward for Qatar

Carbon capture and utilisation (CCU) technologies offer the potential to capture and repurpose carbon dioxide emissions, reducing their release into the atmosphere. This aligns with the broader goal of mitigating climate change and transitioning towards a low-carbon economy [47] . Urban resilience is a key focus, with one document emphasising the importance of building resilience to climate change challenges in urban areas. In particular, the vulnerability of urban infrastructure to climate change impacts, such as sea-level rise, highlights the necessity for sustainable urban planning and development strategies to protect critical infrastructure and minimise risks [51]. Adapting to climate change requires sustainable urban planning and development to ensure the long-term viability of the cities. This includes strategies to address rising temperatures, sea level rise, and other climate-related threats [49].

Collectively, referring to the above texts and Figure 12, these documents contribute to the understanding of the relationship between urban development and climate change in Qatar. They underscored the need for sustainable urban planning and development strategies to address the impact of climate change, reduce carbon emissions, and build resilient cities. By adopting sustainable practices and investing in climate-resilient infrastructure, Qatar can mitigate the risks associated with climate change and ensure a more sustainable future in its urban areas.

Figure 12 Sustainable urban development in Qatar

3.3 Overlay Visualization

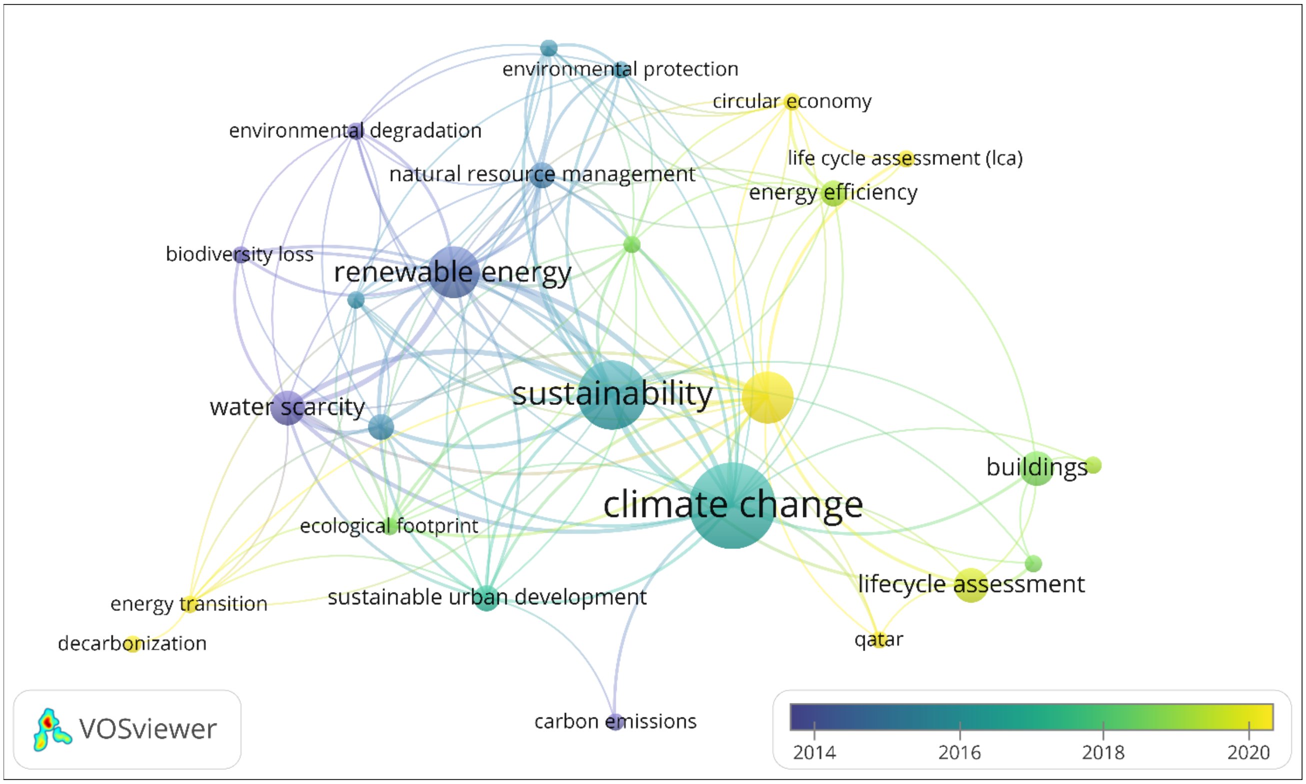

Figure 10: Overlay visualization

The overlay visualisation shown in Figure 13 adds a temporal dimension to keyword analysis, showing how the focus of research has evolved over time. This dynamic view is particularly useful for understanding the emerging trends and shifts in academic priorities. For instance, newer research topics such as "decarbonization", "sustainable economic growth", and "energy efficiency" energy efficiency appear more frequently in recent publications, reflecting global shifts towards addressing climate change through sustainable development practices. On the other hand, foundational topics like "environmental protection" and "natural resource management" might have been more central in earlier studies but continue to underpin newer research. This overlay can help identify how the research community's focus has expanded to include more complex and integrative approaches such as combining economic development with environmental sustainability in Qatar. The temporal insights provided by overlay visualisation are crucial for identifying research gaps that may have emerged as the field has evolved. For example, while the focus on "climate change" and "sustainability" remains strong, there may be opportunities to explore their intersection with newer concepts such as "circular economy" or "smart cities", which are less prominent but increasingly relevant in the context of Qatar's development goals.

4. Best Practices in Addressing Embodied Carbon: Insights from Global Construction Policies

The global construction industry has recognised the importance of addressing embodied carbon, with various countries implementing strategies to mitigate its impact. In Europe and North America, policies and regulations have increasingly mandated the consideration of embodied carbon in building assessments and certifications. Table 1 shows the details of building regulations that incorporate embodied carbon systems worldwide. The United Kingdom is a leader in this area with the development of the Building Research Establishment Environmental Assessment Method (BREEAM), one of the world's most established methods for assessing, rating, and certifying building sustainability. BREEAM includes criteria for evaluating embodied carbon and encouraging the use of sustainable materials and construction practices that minimise carbon emissions. This methodology emphasises a lifecycle approach, ensuring that embodied carbon is considered from the design phase to the end of a building's life [52]. In the United States, the Leadership in Energy and Environmental Design (LEED) certification by the United States Green Building Council (USGBC) has also addressed embodied carbon, although it has historically focused on operational carbon. LEED includes considerations for reducing embodied carbon, particularly through the Materials and Resources credit category. Additionally, the U.S. federal government has begun to integrate embodied carbon considerations into procurement policies, particularly for large infrastructure projects [53].European countries have implemented policies to reduce embodied carbon emissions. For example, Union's level (s) framework is a voluntary reporting framework that encourages the use of life cycle assessment (LCA) to measure the environmental performance of buildings, including their embodied carbon impacts. This framework aligns with the EU's broader goals under the European Green Deal, which seeks to achieve carbon neutrality by 2050 [54]. In Australia and New Zealand, Green Star certification includes the requirements for reducing embodied carbon. These countries have developed guidelines and tools to help the construction industry assess and lower embodied carbon footprints. The Green Building Council of Australia (GBCA) [55] and the New Zealand Green Building Council (NZGBC) actively promote the adoption of low-carbon materials and reuse of building components to reduce emissions [56]. The Netherlands was a pioneer in implementing comprehensive strategies to reduce the embodied carbon in the construction sector. The cornerstone of the Netherlands' approach to embodied carbon reduction is the National Environmental Database (Nationale Milieudatabase), established along with a national calculation methodology for environmental performance. This database manages two critical types of data: environmental impact information for basic construction materials and product-specific data provided through Environmental Product Declarations (EPDs). These data are essential for calculating the environmental impact of building projects using seven online tools integrated into the Dutch construction industry[57][58]. The calculation methodology is based on the European standard EN 15804, and is essential for compliance with the Dutch building code (Bouwbesluit), which mandates that all new building projects exceeding 100 m² must calculate their environmental performance. This regulation drives the adoption of sustainable practices by encouraging product manufacturers to perform LCA analyses and upload their outcomes to the database, ensuring that more accurate data are used in environmental calculations. Since 2013, the Netherlands has required new residential and office buildings of over 100 m² to report several LCA-based metrics, including the total life-cycle embodied carbon, as part of the building permit application process. This requirement is codified in Building Code 2012 [59], which outlines specific methodologies and data usage protocols [57][58].

These regulations were updated in 2018 to include stricter environmental impact ceilings, with the goal of reducing the environmental impact of construction by 50% by 2030. Environmental impact is translated into "shadow costs", which represent the project's overall environmental burden. The maximum shadow cost for new residential buildings has already been reduced to €0.80 per m² by 2021, demonstrating the Netherlands' commitment to progressively tightening regulations to achieve long-term sustainability goals[57] [58].

The Netherlands embraces circular economic principles, particularly in the construction sector. A notable example is Venlo City Hall, which was designed using the 100% disassembly principle. This approach not only facilitates the reuse of materials but also significantly reduces embodied carbon by enabling buildings to be easily deconstructed and repurposed at the end of their lifecycle.[57] Moreover, cities like Amsterdam have been proactive in publishing tools like the "Circular Toolbox", which guides various departments in incorporating circular construction practices. This toolbox includes reference works on themes such as timber construction and material passports, which are critical for promoting the reuse and recycling of materials, thereby reducing embodied carbon [58].One of the Netherlands's most successful implementations of embodied carbon reduction is the adoption of low-carbon concrete technologies such as the use of recycled cement. A specific case involved the marketing of "Freement", a recycled cement product that can reduce the embodied carbon in concrete by 68%, while simultaneously reducing costs by 56%. This innovation is an example of how environment-friendly technologies can offer economic benefits, further incentivising their adoption. Additionally, Dutch Sustainable Public Procurement Policy plays a crucial role in driving the market towards low-carbon solutions. By prioritising bidders who adopt circular economy principles, the government ensures that sustainability is embedded in public sector projects, further reducing the carbon footprint of new development. [57]

The Swedish Transport Authority mandates carbon accounting for all new projects exceeding 50 million SEK. Since the beginning of 2022, the new Act of Climate Declarations has been in effect and requires all new construction projects to include a report on the climate impact of a building. This report must be submitted to the government to obtain approval for the final building permit. This policy was designed to enhance the building sector's understanding of embodied carbon issues. The maximum limits on embodied carbon are expected to be introduced as early as 2027.[60] Additionally, the National Board of Housing, Building, and Planning provides a climate database developed in collaboration with the Ministry of Environment in Finland to calculate climate impact during construction. [61]

Switzerland has a certification label, "Minergie-Eco", for new and renovated buildings that require embodied carbon calculations. All government buildings must be minergie certified. This program offers a free Excel tool for calculating embodied carbon during the early design stages. While Minergie-Eco is voluntary, some public and private organisations, such as the Zurich Cantonal Bank, have made it mandatory for new buildings and major renovations. The City of Zurich has also set a target to reduce the life-cycle embodied carbon in residential buildings by 2050. [60]

Globally, the push to reduce embodied carbon is supported by a growing body of research that highlights the potential for significant emissions reduction through material selection, construction techniques, and design optimisation. Despite these advances, challenges remain in the standardisation of measurement methods and availability of reliable data across different regions. As countries such as Qatar and others in the Middle East seek to align their construction practices with global sustainability standards, the integration of embodied carbon assessments into their building processes is crucial to achieving long-term environmental goals. Figure 14 shows the countries that have implemented or initiated EC in their building codes, making it a mandatory requirement.

To validate the proposed Embodied Carbon (EC) framework for Qatar's construction sector, empirical data and findings from previous studies, such as the Netherlands' National Environmental Database, can be instrumental. Here are some strategies to achieve this validation:

- Utilize Comprehensive Databases: The Netherlands' National Environmental Database provides a robust model for collecting and managing environmental impact data for construction materials. By establishing a similar database in Qatar, researchers can gather empirical data specific to local materials and construction practices, enabling accurate EC assessments.
- Adopt Standardized Methodologies: The Dutch approach uses the European standard EN 15804 for calculating environmental performance, which ensures consistency and comparability across projects. Implementing a

similar standardized methodology in Qatar would allow for reliable validation of the EC framework by ensuring that all assessments are conducted using the same criteria [1].

- Leverage Environmental Product Declarations (EPDs): EPDs provide product-specific data that are crucial for calculating the environmental impact of building projects. By encouraging local manufacturers to produce EPDs, Qatar can enhance the accuracy of its EC assessments, similar to practices in the Netherlands .
- Incorporate Life Cycle Assessment (LCA) Tools: The Netherlands integrates LCA tools into its construction industry to assess the total life-cycle embodied carbon. Qatar can adopt these tools to validate its EC framework by comparing the results with those from established systems, ensuring that the framework aligns with international best practices .
- Benchmark Against International Best Practices: By comparing Qatar's EC framework with those of countries like the Netherlands, which have mandated EC regulations, Qatar can identify gaps and areas for improvement. This benchmarking process can validate the framework's effectiveness in reducing embodied carbon emissions .
- Conduct Pilot Studies: Implementing pilot projects using the proposed EC framework can provide empirical data on its effectiveness. These projects can serve as case studies to demonstrate the framework's impact on reducing embodied carbon in real-world scenarios, offering insights for further refinement.
- Engage in Continuous Monitoring and Feedback: Establishing a feedback loop where data from completed projects are analyzed and used to refine the EC framework can ensure its ongoing relevance and accuracy. This approach allows for continuous improvement based on empirical evidence.

By integrating these strategies, Qatar can effectively validate its proposed EC framework, ensuring it is both robust and aligned with global sustainability standards.

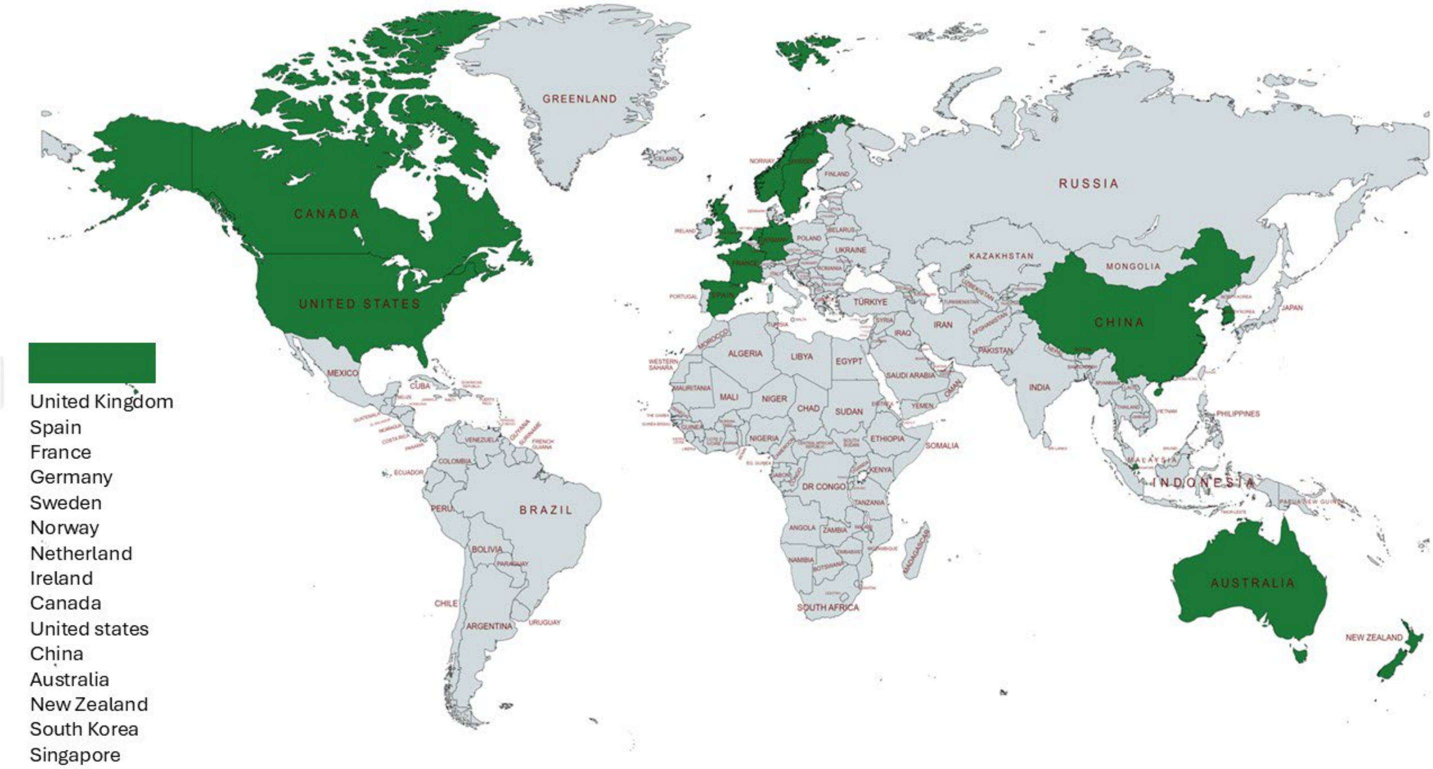

Figure 14 : Energy Codes: A global trend

Table 1: Building regulation that incorporated EC

Region	Policy/ Standard/ Certification	Organization/ Authority	Type	Embodied Carbon Requirement
Global	BREEAM International	BRE Group	Certification	Optional
	Living Building Challenge	International Living Future Institute	Certification	Required
	The Net Zero Carbon Buildings Commitment	World Green Building Council	Commitment	Required
	EDGE Buildings	International Finance Corporation (IFC)	Certification	Optional
Europe	Environmental Regulation 2020 (RE2020) - France	French Government	Regulation	Required
	The Climate Declaration Act for New Buildings - Sweden	Swedish Government	Regulation	Required
	Bepalingsmethode Milieuprestatie - Netherlands	Dutch Government	Standard	Required
	FutureBuilt - Norway	Norwegian Government	Certification	Required
United Kingdom	Whole life carbon assessment for the built environment	Royal Institution of Chartered Surveyors (RICS)	Standard	Required
	The London Plan	Greater London Authority (GLA)	Regulation	Optional
	BREEAM UK	BRE Group	Certification	Optional
North America	Zero Carbon Building Standard - Canada	Canada Green Building Council (CAGBC)	Certification	Required
	Leadership in Energy and Environmental Design (LEED)	US Green Building Council (USGBC)	Certification	Optional
	Local Law 97 - New York, USA	New York Government	Regulation	Optional
	SE2050 - USA	Structural Engineering Institute	Pledge	Required
Asia-Pacific	Green Star Australia	Green Building Council Australia (GBCA)	Certification	Optional
	State Environmental Planning Policy (Sustainable Buildings) 2022 - Australia	New South Wales Government	Regulation	Required
	Whole-of-Life Embodied Carbon Emissions Reduction Framework - New Zealand	New Zealand Government	Policy	Required
	Green Star NZ	New Zealand Green Building Council (NZGBC)	Certification	Optional
	China Green Building Label (Three Star)	China	Certification	Optional
	G-SEED	Korea	Certification	Optional
	BCA Green Mark	Singapore	Certification	Optional

5. Conclusion

This study highlights the urgent need for Qatar to address embodied carbon within its construction sector, which significantly contributes to the country's overall carbon emissions. Through a systematic literature review, this study utilised the PRISMA framework to identify key studies relevant to embodied carbon in Qatar, focusing on sustainability, climate change, and construction practices. By employing tools, such as the VOS viewer, keyword network analysis revealed research gaps, particularly in local studies and data on embodied carbon. These findings demonstrate that a region-specific approach is necessary to effectively measure and reduce embodied carbon in Qatar's built environment.

Globally, the construction industry has increasingly recognised the need to mitigate embodied carbon, with many countries implementing policies and certification systems. Examples include BREEAM in the United Kingdom [52], LEED in the United States, and the European Union's level (s) framework. Countries such as the Netherlands have taken pioneering steps, with mandatory life-cycle assessments (LCA) and comprehensive embodied carbon databases integrated into their building codes. These global efforts offer valuable insights for Qatar, which despite its progress in sustainable initiatives such as the Global Sustainability Assessment System (GSAS), lacks the localised embodied carbon data and regulatory frameworks necessary to drive substantial reductions in carbon emissions from construction.

This study also underscores the importance of a comprehensive embodied carbon database tailored to Qatar's environmental and economic contexts. The lack of localised data remains a significant barrier to the accurate assessment of the carbon footprints of construction materials and processes. Establishing such a database, along with adopting international best practices, such as carbon accounting and LCA, will enable Qatar to develop targeted strategies for reducing embodied carbon in its infrastructure projects, aligning with both national and global climate goals. Table 2 summarises the findings, gaps, opportunities and recommendations for carbon assessment in Qatar

Table 2 Summary of Key Findings, Gaps, Opportunities, and Recommendations for Qatar's Embodied Carbon Assessment

Aspect	Key Findings	Gaps Identified	Opportunities	Recommendations
Embodied Carbon Impact	Embodied carbon constitutes a significant portion of lifecycle emissions in Qatar's construction sector.	Lack of comprehensive and localized embodied carbon data specific to Qatar's construction materials and processes.	High potential for adopting global best practices tailored to Qatar’s unique environmental and economic conditions.	Develop a national embodied carbon database and integrate it into the Qatar National Vision 2030 framework.
Regulatory Framework	Existing initiatives like GSAS partially address sustainability but lack mandatory embodied carbon assessment.	Absence of policies mandating life-cycle assessments (LCA) or carbon declarations for new construction.	Opportunity to establish mandatory EC assessments aligned with international benchmarks (e.g., BREEAM, LEED, Dutch LCA).	Mandate embodied carbon assessments in building codes, leveraging global practices from the Netherlands and Sweden.
Construction Materials	Cement and steel dominate carbon emissions due to energy-intensive production and reliance on imports.	Limited adoption of low-carbon alternatives and inefficient material recycling practices.	Potential for utilizing recycled materials, cement alternatives, and renewable energy in material production.	Promote research and development for low-carbon materials and incentivize the use of recycled resources in projects.
Climate Adaptation	Rising temperatures and sea-level rise exacerbate Qatar’s environmental vulnerabilities.	Lack of coastal protection measures and climate-resilient construction strategies.	Design climate-resilient buildings and infrastructure to reduce embodied and operational carbon impacts.	Implement climate-responsive urban planning and prioritize eco-friendly infrastructure projects in vulnerable areas.
Data and Research	Keyword and bibliometric analyses reveal growing interest in sustainability but limited focus on Qatar.	Lack of systematic studies quantifying embodied carbon in Qatar’s unique climatic and economic contexts.	Collaborate with academic and industry stakeholders to generate region-specific research and promote knowledge-sharing.	Establish partnerships between government, academia, and industry to conduct in-depth embodied carbon studies.

In conclusion, addressing embodied carbon is imperative for Qatar's sustainable development and its commitment to reducing carbon emissions as outlined in Qatar’s National Vision 2030. The findings from this study highlight the urgent need for Qatar to establish a comprehensive embodied carbon database tailored to its unique environmental and economic contexts. This database will serve as a foundational tool for accurately assessing the carbon footprints of construction materials and processes, thereby enabling the development of targeted strategies for reducing embodied carbon in infrastructure projects. To facilitate this transition, Qatar must prioritize several key actions: first, the establishment of localized data collection mechanisms to fill the existing research gaps; second, the adoption of international best practices in carbon accounting and life-cycle assessments (LCA) to inform policy and regulatory frameworks; and third, the integration of rigorous embodied carbon assessments into the construction sector's regulatory landscape. By learning from global examples, such as the mandatory LCA in the Netherlands [57]and established certification systems like BREEAM[52] and LEED [53], Qatar can enhance its environmental policies and drive substantial reductions in construction-related carbon emissions. Future work should focus on fostering collaboration among stakeholders, including government, industry, and academia, to promote knowledge sharing and innovation in sustainable construction practices. Additionally, ongoing research should aim to continuously update and refine the embodied carbon database, ensuring that it reflects the latest advancements in materials and technologies. By committing to these actions, Qatar can effectively manage its carbon footprint, contribute to global climate change mitigation efforts, and support sustainable growth in its construction sector.

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