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Review

The Role of Using Green Concrete Materials for the Egyptian Residential Buildings Sector to Achieve Sustainable Development Goals

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Abstract

Rapid urbanization in the Egyptian building sector has led to substantial consumption of conventional concrete material (CCM). Therefore, the use of sustainable construction materials has attracted considerable attention among stakeholders seeking to achieve sustainability. This paper investigates the use of green concrete materials (GCMs) in residential buildings to support the achievement of Sustainable Development Goals (SDGs). We employ an assessment-based approach to investigate the relationship between GCMs and SDGs. Green concrete materials sustainability framework (GCM-SF) was developed from a comprehensive literature review and case studies. We analyzed 27 green concrete materials sustainability indicators (GCM-SI) using a five-point scale and a score matrix to define the contributions and relationships among GCMs, SDGs, and the three sustainability pillars. This study shows that the use of GCMs in residential buildings (RBs) makes a significant contribution to achieving SDGs. Results indicate that the highest contributions are 92% for SDG 12, 85% for SDG 11, 85% for SDG 6, 77% for SDG 9, 74% for SDG 8, 70% for SDG 3, and 70% for SDG 7. Additionally, the lowest contributions to GCM's environmental indicators were observed for SDG4, SDG10, and SDG16. This can help environmental and construction stakeholders apply new rules and regulations for the use of GCMs in future residential projects. Social sustainability of RBs and applying GCMs for different building types needs further investigation in the future.

Keywords: sustainable development goals; green concrete; residential buildings; construction materials; Egypt

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1. Introduction

Rapid population growth is associated with increased construction activity, thereby increasing the number of residential buildings worldwide. The United Nations-Habitat (UN-Habitat) reported that approximately 40% of the world's population will live in housing by 2030 [1]. In 2022, the new housing number reached 96,000 units per day, meeting global demand driven by the nation's urbanization. This led to an exponential increase in construction activity, particularly in the residential sector [2,3]. The construction industry is strongly responsible for achieving sustainability in the triple bottom line: economic, social, and environmental [3,4]. At the same time, the sector is a significant contributor to economic growth, accounting for 5–10% of employment and generating 5–15% of GDP

(UNEP, 2018). The RBs sector consumes non-renewable energy and natural resources; for example, it causes approximately 40% of energy consumption, solid waste generation, 12% and 16% of water and freshwater use, respectively, and about 30% of greenhouse gas emissions (GHG) worldwide [3,5,6] (UNEP, 2018). However, countries rely heavily on concrete to meet urbanization needs for socio-economic growth, particularly those experiencing rapid population growth and rapid urbanization (United Nations, 2017) [3]. Therefore, concrete and cement are among the most widely used artificial materials and have become the second fastest-growing industry worldwide [7]. From an environmental perspective, the use of conventional concrete materials (CCM) will deplete natural resources and produce adverse ecological effects that are expected to persist for the next few decades [8]. Conversely, concrete is considered an essential building material with several sustainability advantages, including strength, durability, workability, and cost-effectiveness. The most commonly used type is Portland cement concrete (PCC), with a global production rate of approximately 6 billion tons [7,9]. Demand for concrete has increased due to its versatility in many structural applications, which resulted in significant growth in the cement industry, particularly in the production of Ordinary Portland Cement (OPC). Unfortunately, this growth has had harmful effects, resulting in high energy loads and CO_2 emissions [10–12]. The production of OPC requires substantial energy, as the materials, such as calcareous and argillaceous substances, must be melted at 1700 °C. Furthermore, the chemical reaction that decomposes limestone ($CaCO_3$) into ($CaO + CO_2$) significantly contributes to the large carbon footprint. For each 1 ton of cement produced, approximately 0.9 tons of carbon dioxide are generated, resulting in approximately 21.6 billion tons globally [13]. According to the World Energy Outlook, cement production accounts for approximately 8% of anthropogenic carbon footprint [8,9,14]. Therefore, in the construction sector, the continued extensive consumption of these resources may undermine future sustainability [15]. Figure 1 shows global cement production from 2015 to 2022, in billion metric tons.

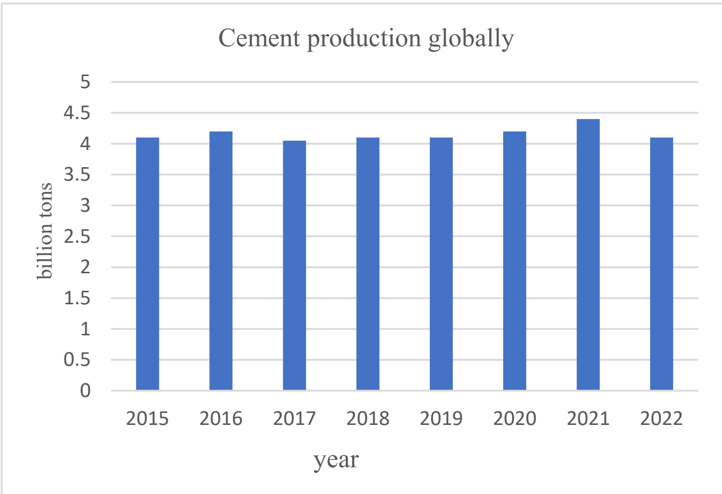

Figure 1. Global cement production [15,16].

Currently, the need for using sustainable construction materials with low environmental impacts and cost-effectiveness is increasing, and the use of GCMs is highly recommended to meet the nation's urbanization needs [17,18]. However, GCMs refer to concrete materials that contain recycled materials in their components and/or have low environmental impact during production and manufacturing, and can also incorporate innovative technologies and eco-friendly materials [19–21]. Therefore, reusing recycled industrial waste as a substitute for supplementary cementitious materials (SCMs) is an effective strategy for reducing cement use, supporting environmental protection, conserv-

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ing energy, and mitigating CO_2 emissions. Consequently, partially substituting OPC with various SCMs, such as fly ash (FA), ground granulated blast furnace slag (GGBS), and silica fume (SF), reduces environmental impacts. For example, integrating FA and GGBS can reduce CO_2 emissions by 70%. Similarly, alkali-activated concretes (AAC) reduce GHGs by approximately 70–75%, while high-performance concrete (HPC) can have enhanced durability and strength when compared to OPC concrete (OPCC) [22,23]. Therefore, reusing recycled materials as construction and demolition waste (CDW) is an effective strategy for reducing cement and natural aggregate consumption, supporting environmental protection, conserving energy, and mitigating CO_2 emissions [11,24,25].

Recently, the use of GCM as an environmentally friendly material in the residential sector and the partial replacement of CCMs in the early design stages have shown promising sustainable solutions for reducing CO_2 emissions [4,8,26–28]. Additionally, selecting appropriate concrete materials for residential buildings is crucial for achieving Sustainable Development Goals (SDGs) [29]. However, most prior research focuses on strength and durability without considering social sustainability, an area that warrants greater attention and investigation to improve occupants' quality of life [28,30]. Therefore, green and eco-friendly materials that create a sense of place in the places where people live and conduct their activities can improve the occupants' quality of life. Meanwhile, reducing natural resource and energy consumption, as well as emissions, should be considered to achieve a 50% reduction by 2030, in line with the Paris Agreement climate goals [1,2,4,31]. Therefore, prioritizing sustainable procurement of construction materials is essential to meet current construction demands while preserving natural resources for the future. Thereby, it enables sector stakeholders to meet design and development needs without imposing environmental burdens throughout the building's life cycle [30,32].

Despite Egyptian regulations providing clear guidelines for CCM design, GCM adoption remains limited in the residential sector. Concrete codes primarily focus on structural safety and prescriptive standards for traditional mixes, offering limited options for GCMs and the use of recycled aggregates. In contrast, the lack of consensus in the construction industry regarding the sustainability role of GCMs has led to differing understandings among stakeholders, including whether implementing GCMs can achieve SDGs and what opportunities and obstacles arise in its use in the residential sector. These require a sustainability framework that highlights the role and effects of using GCM as an eco-friendly material. Therefore, the current study aims to identify the sustainability aspects of using GCMs for RBs to achieve SDGs by investigating the contribution relationship and developing a GCM-SF, thereby aiming to answer the following questions: how can the use of GCMs contribute to achieving SDGs in Egyptian residential buildings, and what are the high and low contributions of GCM-SI to SDGs in the three sustainability pillars? This study represents the first attempt to examine the contribution of using GCMs and developing GCM-SF to integrate the sustainability pillars and SDGs for Egyptian residential buildings. This framework presents a novel tool and a starting point that helps stakeholders, including environmental scientists, engineers, architects, material manufacturers, and regional developers, investigate the role of GCMs in achieving sustainability in the RBs sector. Moreover, the variety of material strategies and building types offers opportunities for future research in this topic at both local and global scales.

2. Literature Review

2.1. Construction Materials and Sustainable Development Goals

Conventional construction activities and the consumption of raw materials, especially for residential buildings, harm communities from both environmental and social perspectives, necessitating extensive stakeholder engagement between construction and environmental organizations [33]. Several previous studies have demonstrated that the use of sustainable construction materials is a crucial strategy for improving environmental protection by promoting the recycling and reuse of (industrial, agricultural, and municipal) wastes, as well as reducing energy use and CO_2 emissions [34–37]. In this regard, analyzing the evaluation of the selection of appropriate sustainable materials became a crucial starting point. This should be considered in all phases of RB projects, from the early design stage through construction, operation, renovation, maintenance, and demolition throughout the building's lifespan. A multidisciplinary approach grounded in sustainable solutions offers numerous benefits for the environment, economy, and social aspects [38].

According to the World Green Building Council (WGBC), increasing the number of recommendations for environmental scientists, engineers, and designers to integrate SDGs into sustainable building design solutions yields numerous societal and health benefits, particularly in the residential sector [39]. In this context, the study by Sánchez-Garrido et al. [40] focuses on applying modern construction methods that utilize eco-friendly materials to enhance the economic benefits of conventional construction materials and methods.

Therefore, the studies of Goubran et al. and Goubran [41,42] developed two mapping tools to examine sustainability in the design process of building projects, focusing on achieving SDG4, SDG6, SDG7, SDG9, SDG11, SDG15, and SDG17. They investigated the relationship between the building design phase's direct and indirect impacts, which aligned with (SDG6, SDG7, SDG9, and SDG17), and (SDG4, SDG8, SDG11, and SDG15), respectively. Moreover, analytical tools for integrating design-phase approaches that align with the SDGs' vision are proposed. They found that 17% of SDGs were directly related to construction and 27% were indirectly related. They concluded that construction activities are most important for achieving SDG11, SDG6, and SDG7. Additionally, Sánchez-Garrido et al. and Zastrow et al. [40,43] analyzed the economic and environmental aspects from a design perspective and concluded that constructing high-quality housing without increasing costs is feasible; furthermore, Panesar et al. investigated optimizing material consumption and reducing the carbon footprint [44].

2.2. Green Building Materials and Sustainable Development Goals for Residential Buildings

According to the WGBC (2019) report, green building materials are associated with achieving the nine goals of SDGs. Additionally, Leadership in Energy and Environmental Design (LEED) emphasizes the use of green building materials and the efficient use of energy and water, which significantly contribute to achieving the SDGs [39]. In this context, Wen et al. [45] propose a mapping tool to quantify the relationship between green buildings and SDGs, focusing on SDG3, SDG7, SDG11, and SDG12, and identify the most closely related goals. They note that target 7.3 serves as the intermediate pathway in green building rating tools. The contributions to SDG9, SDG13, and SDG15 were relatively small, as validated by a case study in a LEED-certified building. Furthermore, the study by Secher et al. [46] suggests that the choice of green building materials has a significant direct and indirect impact on the selection of appropriate concrete materials for several goals, including SDG3, SDG6, SDG7, SDG8, SDG9, SDG11, and SDG12. Similarly, Alawneh et al. [4] identified a strong relationship among the SDGs related to energy and water efficiency; they found that the contributions were significant for [SDG6, SDG9, SDG12, SDG13, and SDG15]. They propose an evaluation framework to help consider the previously mentioned SDGs throughout the building project life cycle.

Moreover, many studies recommend sustainable practices and tools for implementing SDGs by prioritizing specific goals [37]. In the same context, the study by Omer et al. [47] developed a conceptual framework for the contribution of SDGs and building materials and found that selecting building materials is considered an important step to achieving SDGs. They conclude by emphasizing the importance of developing a multi-criteria optimization tool to assess the material's efficiency during the early construction stage Additionally, they clarify how green buildings can play a significant role and find that there are nine goals of the SDGs, including "SDG3, SDG7, SDG8, SDG9, SDG11, SDG12, SDG13, SDG15, and SDG17," that can contribute to meeting sustainable development goals. Despite the environmental perspective that rapid urbanization and construction activities in RBs have adversely affected ecosystems and biodiversity, a study by Opoku et al. [30] highlights the importance of applying GCMs to enhance infrastructure and biodiversity evaluation to achieve the 15 goals of SDGs.

Meanwhile, the residential application has a distinctive typology that differs from that of other structures, with various considerations, including building aesthetics, occupant comfort, cost-effectiveness, and building lifespan. Although concrete compressive strength for the RB construction process is often given greater attention, the quality of concrete used for finishing surfaces is also important. Therefore, Agbesi et al. and Goubran [42,48] are focused on adopting sustainable practices for construction procurements to achieve SDGs in construction projects. However, when the material is used for purposes such as decorative walls and polished floors, CCM consumption increases. Therefore, the use of green, sustainable materials rather than conventional materials is strongly promoted to improve material energy efficiency and address the sector's decarbonization challenge [18]. Despite this, constructing low-rise RBs requires smaller sizes, scales, and loads than those of other building types. Still, safety and well-being are essential for selecting appropriate green materials. In this regard, the selection of green building materials is a vital strategy for improving a building's sustainability performance and informing decision-making regarding new policies and regulations [39]. Sánchez et al. [40] applied sustainability principles to building structures through multi-criteria decision-making to evaluate modern and innovative construction methods. They compared various modern construction techniques for residential buildings to assess sustainability using 38 indicators that address environmental and economic dimensions. Furthermore, the study by Invidiata et al. [38] highlights the importance of selecting RB designs and materials using a multi-criteria decision-making approach to achieve more sustainable buildings. In the last few decades, the number of residential buildings in Egypt has increased, necessitating the use of sustainable building materials. However, many strategies support the adoption of sustainable practices; there remains no clear framework for identifying the needs for sustainable concrete materials suitable for residential applications [18,26].

2.3. Green Concrete Materials, Sustainability, and Sustainable Development Goals

Since sustainable concrete materials were introduced in the 2000s, the sector has undertaken measures to mitigate the adverse impacts of CCMs. These are considered eco-friendly materials that can be enhanced to contribute to the 2030 Agenda established in 2015. However, a GCM is defined as a concrete material produced from eco-friendly materials based on sustainable strategies and practices [7,8,49–51]. Notably, concrete is widely used in RBs for its numerous advantages, such as high durability, fire resistance, and energy efficiency, making it an optimal choice for residential construction projects. Despite recent increases in global recommendations for using GCMs, which have garnered tremendous attention worldwide, there remains a need for the materials' sustainability evaluation to clarify which actions will contribute to achieving SDGs. In this context, the absence of a GCM conceptual standards definition prevents theoretical underpinnings from being detailed, allowing for various interpretations from different perspectives. The study by Burgass et al. [52] discusses the measurable systems that depend on category contributions

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in conceptualizing sustainable development. According to the life cycle assessment (LCA) is "the compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle." Similarly, Anastasiou et al. [53] consider the LCA an accepted tool for assessing and comparing the environmental benefits.

Furthermore, Teh et al. [54] identified GHG from geopolymer, concrete, and cement in Australia across the four main LCA stages. Additionally, Marinković et al. [55] identified and compared different GCMs with the same compressive strength and workability using LCA, considering construction activities, transportation, and local materials in Serbia. The study demonstrated that alkali-activated FA concrete with natural aggregate (NA) and high-volume FA, as well as the RAC mix with high FA content, exhibited the best environmental performance, whereas the RAC mix with cement binders performed the worst. In the same context, the LCA applied by Borghi et al. [56] quantifies and evaluates energy use and CO_2 emissions across all construction stages, including material consumption, energy use, and environmental emissions. Additionally, Atmaca et al. [57] assessed primary energy consumption and CO_2 emissions using a building LCA for the two RBs in Turkey.

However, RBs generate high value across both economic and environmental pillars and often involve more intensive material consumption than necessary. Therefore, achieving the same mechanical durability and strength of concrete with low cement content in the building's structural works is feasible with RAC. In this regard, Guo et al. [58] identified the sustainability of the GCMs, which depends on their ability to develop alternatives that reduce OPC use. Meanwhile, Marey et al. [26] investigated the effects of using GCMs in low-rise residential buildings in Egypt. They identified the role of substituting GCMs in RBs for concrete in the early design stage and the reduction in carbon emissions from replacing OPCC with RAC for selected non-structural building parts after improving the original building design.

According to the UN (Resolution 70/1-Transforming our world), the 2030 Agenda for Sustainable Development (SD) specifies the '17 SDGs and their 169 targets. In this regard, Rajabi et al. [59] integrated the sustainability pillars with the SDGs agenda to implement them at the regional level, based on stakeholders' national regulations and specific priorities. Additionally, Sharma et al. [60] identified and mapped the parameters for the large-scale use of phase change materials in concrete. The study showed that significant use promotes the potential for achieving (net-zero-ready buildings) during the lifespan, which contributes to SDG 7, SDG 11, and SDG 12, and realizing SDGs. Gettu R. et al. [61] propose a framework for selecting concrete mixture properties based on sustainability criteria, using objective indices such as energy intensity, integrated CO_2 emissions, and concrete durability parameters. In the same regard, Opon et al. [62] explain the sustainability of the concrete material indicators framework, focusing on integrating performance and operationalized sustainability indicators. The framework identifies the indicators' causality, establishes links between sustainability pillars and SDGs, and helps select the most appropriate indicators for evaluation.

However, the LCA was performed for different binders, and by-product materials such as fly ash and slag were used as an OPC substitution. Consequently, incorporating CDW into the production of recycled concrete components as part of the concrete mixture is considered an environmentally friendly manufacturing process. In this regard, Tam et al. [63] explore the possibility of utilizing CDW as recycled aggregates (RA) for infrastructure development. The RA specifications and quality define the CDW potential for RAC, which could offer substantial environmental benefits by reducing CO_2 emissions and facilitating civil construction projects for roadways and pavements. As such, they strongly suggest implementing RA materials on a larger scale in construction initiatives. Therefore, the use of RAC-based CDW is considered an example of GCM sustainability behavior. It reduces cement consumption and energy use by 50–75%, and results in reductions in landfill disposal and CO_2 emissions by 10–30% [23,64,65]. Furthermore, Alami et al. [66] investigated the role of innovative solutions and new technologies, such as 3D concrete printing. The study evaluated three cementitious mixtures and observed cost reductions of 78–60% and a water reduction of approximately 20%. However, various studies have compared different building materials and positively reported that GCMs are more environmentally friendly and have the same functionalities and properties as CCMs for building-life services, as investigated by Al-Mansour et al., Rahal K., El-Hawary et al., and Ai et al. [67–70].

At the same time, there is limited awareness of GCMs, which remains a relatively new approach that requires greater adoption across public and private sectors in the construction industry, as well as increased attention to their roles in achieving SDGs [71]. Additionally, it is necessary to identify the social, economic, and ecological behaviors of materials among the construction industry stakeholders. Cooperation in implementing new rules and regulations is needed from all parties, including policymakers, regional developers, engineers, architects, environmental scientists, builders, and market suppliers [60,71,72]. Consequently, assessing sustainability needs requires a framework that enables public and private organizations to develop new policies and technical standards. However, GCMs are considered a sustainable, environmentally conscious choice that offer a range of benefits for the RBs industry. Therefore, many obstacles to the use of GCMs in the residential sector for achieving sustainability remain, including the need for trained and skilled labor, supplies, and safe working conditions, as well as the absence of GCM-specific regulations, which warrant further investigation in future research [40].

3. Materials and Methods

The assessment-based approach is developed and applied to investigate the contributions of GCMs and SDGs and to develop a GCM-SF that integrates two global sustainability perspectives within the Egyptian residential buildings sector. To achieve the study objectives, we employed a multi-pronged methodology comprising the following steps. First, a comprehensive literature review was employed to examine the roles of various types of GCMs in the context of sustainability pillars and SDGs. Second, we identified and developed a GCM-SI for Egyptian residential buildings based on the concrete code, green building rating systems, government reports, Egyptian residential building regulations, and case study data and information in Egypt. We applied a five-point scale based on the literature and adapted it to investigate the relationships among GCM-SI, SDGs, and the three sustainability pillars. Third, we identified the contribution score to inform the proposal of GCM-SF for the RBs sector. This was followed by an analysis of GCM-SF's effectiveness on the Egyptian residential building case studies in encouraging scalability contributions to achieve SDGs in future residential projects. To accomplish this, the following stages are considered:

3.1. Identify the Green Concrete Materials Sustainability Indicators for Residential Buildings

A comprehensive literature review was conducted using Google Scholar, Scopus, and ScienceDirect, guided by screening criteria aligned with the current study scope. The selecting criteria were the relevant paper within the year range that started in 2017, ensuring that research papers investigating SDGs were published in the academic literature two years after the UN agenda began in 2015 and five years after the definition of GCMs. Therefore, the selected studies ensure that the current research will address existing gaps and identify new opportunities for further investigation. A literature review identified potential GCM sustainability indicators from 135 papers, as reported in previous research, using the criteria shown in Table 1. The abstracts and conclusions of these papers were reviewed to ensure that the articles were the most relevant to the study topic. After an initial screening, the review was narrowed to 85 peer-reviewed journal articles to demonstrate proposed indicators. Furthermore, we reviewed government reports and official regulations governing the Egyptian residential building sector, using official documents and data obtained from previous case studies, and discussed the use and selection of GCMs in real and existing residential buildings, like in the work by Marey et al., 2022 and Marey et al., 2024 [26,73].

Table 1. The literature review keywords.

Keywords	Synonymous
Green concrete	Eco concrete, sustainable concrete, conscious concrete, friendly concrete materials
Supplementary cementitious materials	Supplementary cementitious materials, RAC, recycle waste content,
Concrete performance	Concrete behavior, properties, strength, durability, maintainability
Waste reduction	Waste recycling, CDW, by-product
Environmental impact	CO_2 emissions, pollution.
Concrete component	Sand, natural aggregate, water, and gravel.
Residential buildings (RBs)	Green residential building
Sustainable construction materials	Sustainable construction methods, alternative green materials, code, and standards.
Sustainability pillars	Environmental, social, economic
SDGs	17 goals and 169 targets.

However, the first step aims to define and categorize the most essential indicators of GCM that could help achieve SDGs. Therefore, the inclusion criteria for the selected papers focused on keywords that were derived from the perspectives of (sustainable construction materials, green concrete, sustainability indicators, residential building, SDGs and their targets, RAC, natural resource consumption, supplementary cementitious materials (SCMs), energy efficiency, waste management, and cost-effectiveness), as shown in Table 1. Additionally, GCMs' performance, including durability, strength, maintainability, and workability, was reviewed within the limitations of its suitability for residential applications to identify the parameters of sustainability indicators. Furthermore, during the selection process, evidence from Egypt was considered despite the limitations of the studies, and therefore, similar contexts were also included. In contrast, studies that discussed CCMs or other concrete types unsuitable for residential applications, as well as studies addressing other construction applications without a clear explanation or transferability, were excluded.

Selection Criteria for Green Concrete Materials Sustainability Indicators

Most of these indicators were obtained from a literature review and are supported by data and information from the Egyptian case study. Indicators were derived by identifying the parameters and metrics for GCMs and linking them to sustainability pillars and SDGs as the governing context. We ensured that the indicators applied specifications and standards based on the concrete code and green building rating systems, such as the Green Pyramids Rating System (GPRS) for sustainable building practices in Egypt, Egyptian government reports, and residential building rules and regulations [73]. Consequently, this helped develop the GCM-SI set and ensured its validity for long-term implementation in future RB projects. Indicator synonyms are filtered and summarized to improve transparency and clarity. Furthermore, we integrated GCM indicators by combining several indicators into a single one, such as natural resource consumption (e.g., raw materials and water) and CO_2 emissions from cement production, energy use, and transportation [74]. While quantitative reporting was incomplete or non-comparable across sources, data and information from previous Egyptian residential case studies, which were investigated and validated by construction experts, were applied and clarified to preserve transparency. Therefore, criteria for the selection of indicators are based on the following:

- Ensuring that they are applicable for implementation in RBs.
- Supported by accessible data, thereby enhancing their value for implementation, reliability, and validity.
- The indicators' sustainable behaviors are easily understood and familiar to a wide range of residential sector stakeholders from diverse backgrounds and realms.

3.2. Developing the Green Concrete Materials Sustainability Indicators' Contribution Score

After identifying GCM indicators and analyzing relationships among the three sustainability pillars and SDGs, we classified each indicator by pillar (environmental, economic, or social). The contribution score was developed to assess the link between the GCM-SI and goals [75].

3.2.1. Scoring Procedure

In the current study, the cumulative contribution score was calculated using a scoring matrix that assesses the relationship between GCM-SI and the achievement of SDGs.

We developed and applied a scoring approach to quantify contributions of relevant indicators, using RBs extracted and aligned with their matching sustainability pillars. The data were collected from 85 peer-reviewed papers and regulatory sets for the Egyptian residential case study. We assigned a five-point scale to the contribution level for each indicator–SDG pair. The relationship was mapped and assigned to a scale (1–5), where 1 represents a very low contribution and 5 a very high contribution. A score of (very high) (5) indicates a strong, well-supported contribution, meaning the indicator demonstrates a clear, meaningful effect aligned with the SDGs' intent, based on the available evidence. Conversely, a score of (very low) indicates that the contribution pathway is weak, indirect, or poorly supported in the evidence base. Furthermore, a color scheme was applied to clarify and identify the higher and lower contributions in green, gray, and yellow categories, as shown in Table 2.

However, the indicators differ in units, magnitudes, and measurement approaches; therefore, all extracted indicator values were normalized (min–max) prior to scoring to enable consistent comparison across indicators and SDGs. Consequently, a threshold-based approach was used to identify strong linkages between SDG-level outcomes by counting indicator relationships. Finally, we calculated indicator–SDG final scores to determine cumulative contributions, to identify the (highest and lowest) contributing indicators, and to examine the overall contribution patterns of GCM to SDGs achievement in the Egyptian residential sector. Therefore, each indicator was scored and graded in each table cell to clarify the relationships among the SDGs, as shown in Table A1 in Appendix A.

3.3. Develop the Green Concrete Materials Sustainability Framework

This step proposes a framework for investigating and identifying the contributions of GCM-SI, sustainability pillars, and SDGs. Therefore, we quantified the cumulative contribution score to support and highlight the comparative interpretation, indicating which indicators contribute most/least to SDGs achievement in the context of RBs [76]. The framework was analyzed and discussed in the context of the potential of SDGs and three sustainability pillars. The analysis reveals the indicator's behavior that increases sustainability performance and identifies the interrelation improves the strong contribution level of GCMs' indicators.

Table 2. Contribution score between GCM, SDGs, and sustainability pillars.

GCMs Sustainability Score for SDGs	Level to Achieve SDGs
1	Very Low
2	Low
3	Moderate
4	High
5	Very High

Finally, the GCM-SF aims to evaluate the scalability of GCMs' role and to apply knowledge-based decision-making to achieve SDGs in the future of the Egyptian RBs sector. Figure 2 illustrates the current research methodology. GCM-SI behavior and its links to the pillars and SDGs are assessed using a five-point scale to identify the most significant relationships indicative of sustainability, and the framework is grounded in verifiable sources; however, limitations and challenges were encountered. For example, the contribution scoring uses an ordinal 1–5 scale, which provides robust prioritization and comparison but does not represent exact effect sizes. Furthermore, the case-study component relies on a limited regulatory set and residential context, which strengthens contextual relevance but may limit direct generalization, and requires further modification and updating to apply to other building types and regions.

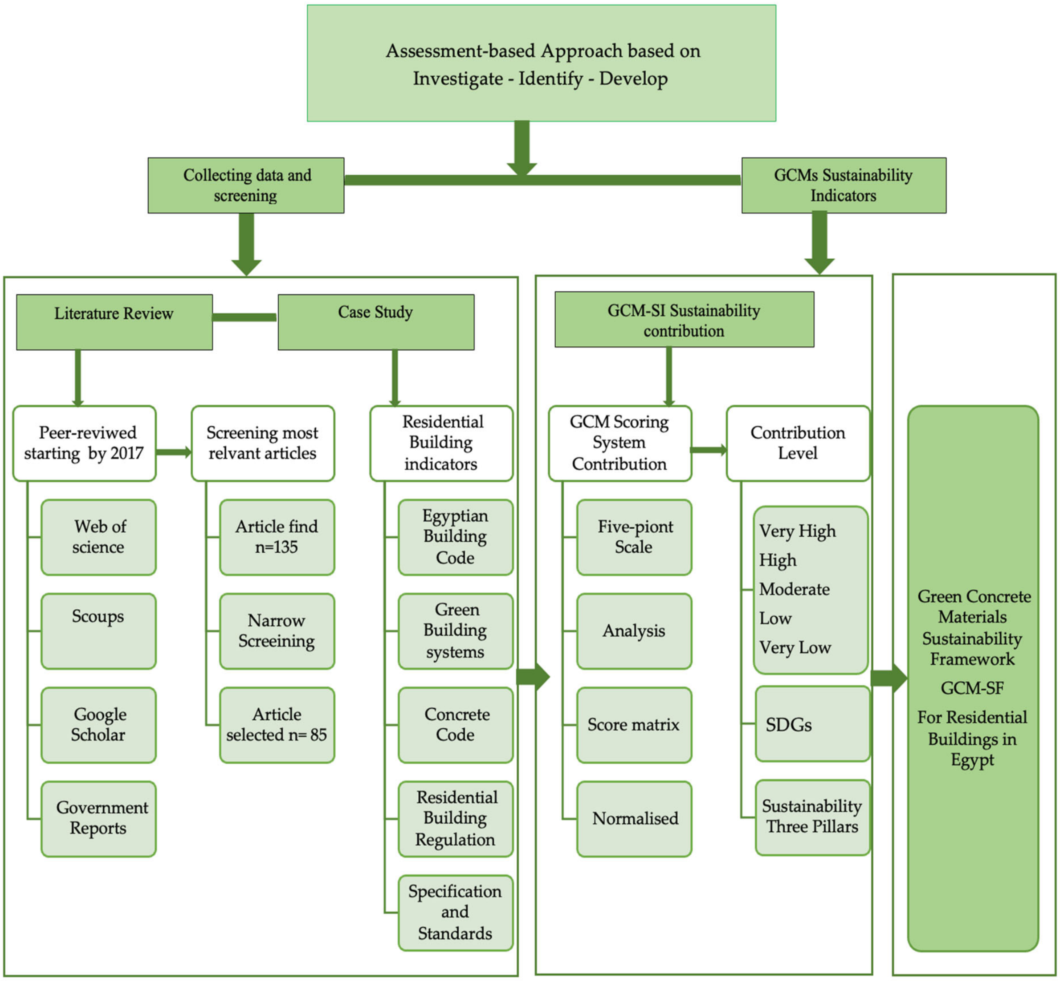


Figure 2. Research methodology.

4. Results and Discussion

4.1. Green Concrete Material Sustainability Indicators

This section identifies GCM's sustainability indicators and examines the most significant indicators for achieving sustainability. We identified 27 indices to clarify and facilitate understanding of the materials' contributions after summarizing and combining the indicators. We proposed a comprehensive list of GCM-SI, which were selected based on their relevance to realizing sustainability, alignment with concrete codes, green building codes, and Egyptian residential regulations, ensuring these indicators capture environmental, economic, and social benefits of using GCMs in RBs. We found that CO_2 and GHG emissions, natural resource consumption, non-renewable energy use, occupant comfort levels, cost-effectiveness, and cement consumption have received considerable attention in previous research. Therefore, we identified the contribution level, considering that increasing the number of RBs will promote significant advantages for replacing CCMs with GCMs in the future Egyptian residential sector.

4.1.1. Egyptian Residential Buildings Sector

In the Egyptian residential building context, requirements for sustainable concrete were applied in accordance with the concrete code and performance standards for durability, compressive strength, and local availability, particularly those with recycled content, therefore considering the implementation of the most common building type, which aligns with the government's development strategy priorities. We found that the most common types of Egyptian RBs are multi-family buildings, townhouses, villas, and single-family houses, particularly in Egypt's new cities. For example, multi-family buildings typically consist of four to six stories and often include a shared courtyard and amenities such as backyards, garages, and green spaces. For example, by 2021/2022, the total number of residential units reached 246 thousand, with investment totaling 143.5 billion Egyptian pounds (LE), compared to 2020/2021, which accounted for 336.3 thousand units and 150 billion pounds. Figure 3 shows the distribution of building types by construction type. Furthermore, economical housing reached 139.8 thousand units which is 56.8%, followed by average housing, luxurious housing, and above average housing which are 69.8, 22.6, and 13.8 thousand units, which recorded approximately 28.4%, 9.2%, and 5.6%, respectively, of the total residential units by the year 2021/2022 [77].

The various types of RBs encompass a wide range of citizens and aim to improve the quality of life for all. The distribution of residential types by public and private sectors is shown in Table 3. For example, Economic Housing is designed for youth and low-income individuals, typically comprising a total area of 90 square meters, and typically consisting of three rooms. Meanwhile, the Above-Average and Average Housing areas are between 100 and 150 m in size, consist of three rooms, and are designated for middle-income residents. On the other hand, for high-income citizens, Luxury Housing is typically villa-style, with a private garden within a closed compound with a security system. The results show that the Cairo governorate ranked first in both the public and private sectors, with 50.1 and 26.5 thousand units, respectively, representing 38.3% and 23% of the total.

Table 3. Distribution of residential types by public and private sectors by 2021/2022.

Unit Types	Public/ Thousand Units	%	Private/ Thousand Units	%	Total	Investment/ Billion Pounds
Economic Housing	97.30	74.5%	42.5	36.8%		
Average Housing	16.30	12.5%	53.5	46.3%		
Above-Average Housing	00.14	0.1%	13.7	11.9%		
Luxurious Housing	16.80	12.9%	5.8	5%		
Total	130.50	100	115.5	100	246.1	143.5

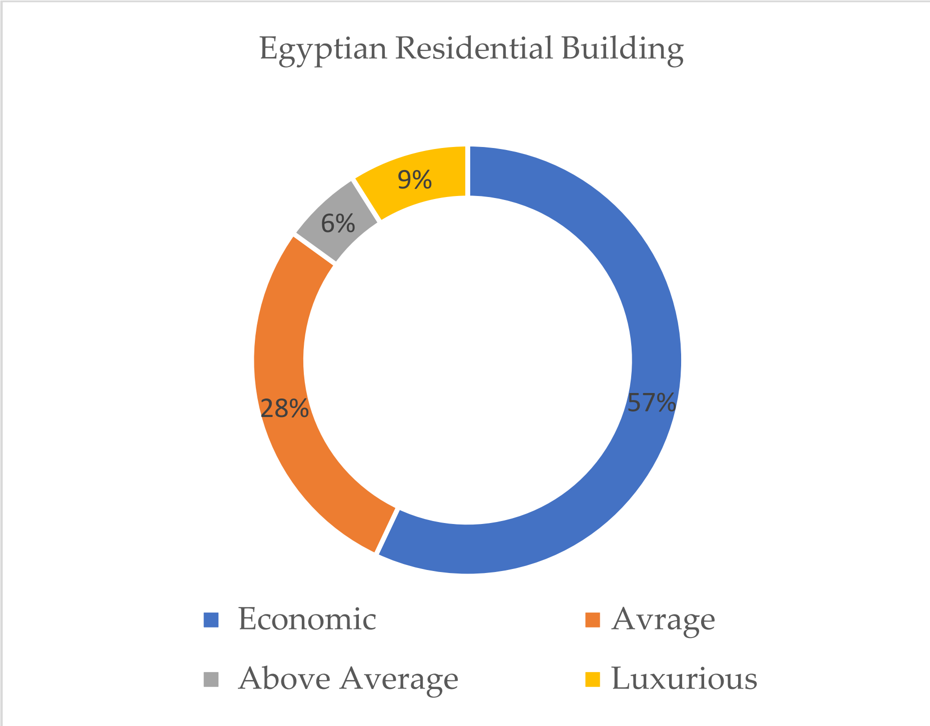


Figure 3. Distribution of residential building types in Egypt, 2021/2022 [77].

Therefore, investigating the types of RBs can provide a comprehensive understanding of how to apply new rules and regulations for the use of GCMs to promote sustainable construction practices in the future.

4.1.2. Residential Buildings Features for Using Green Concrete Materials

Sustainable construction is increasingly important in residential projects, with stakeholders focusing on reducing energy consumption, maintenance, and operational costs. We found that increasing the number of residential buildings can be an opportunity to use alternative, sustainable materials and innovative solutions [18,76]. In the same regard, using GCM as an eco-friendly material for RBs has garnered significant attention due to its diverse material properties and flexible design, which enhance sustainable practices in selecting concrete materials for RB construction [78,79]. Accordingly, the most important RB features include building aesthetics, size, load requirements, thermal and acoustic considerations, customization, durability, budget constraints, building regulations, and the occupants' interior comfort [26,80–87]. Therefore, the RB features selected for GCMs provide various functionalities and versatility across several building components, making them ideal for RB applications [26,88,89].

4.1.3. Green Concrete Strategies and Types

Regarding GCM suitability for RBs, we found that the most common and eco-friendly concrete strategies focus on low primary energy use, use of alternative raw materials, and use of chemical admixtures [23]. For example, partial replacement with SCMs can affect by-product manufacturing waste, including FA and SF from glass production and GGBS from steel manufacturing [64]. Meanwhile, using RAC made with CDW reduces waste disposal to landfill by (50–75%) and embodies carbon by approximately (10–30%), [23,65,90]. In the meantime, these materials can be used in multi-family apartment buildings to increase occupant comfort by providing the same durability and strength for both structural and non-structural works, considering reinforced and non-reinforced concrete in various building parts [22,23]. Additionally, the various types of GCMs exhibit different mechanical properties, strengths, durability, and workability, which promote their widespread use across various strategies and make them suitable for RB codes and regulations [91,92]. The comparison of the LCA between GCMs and CCMs provides a crucial understanding of environmental and economic aspects of RAC through the RB, which should be considered during the building lifespan, starting from the early design stage until demolition, and materials' disposal to the landfill [93–96]. Furthermore, it is necessary to incorporate socioeconomic factors by integrating sustainability perspectives into the management of construction practices and RB factors [97,98].

Despite the positive effects of GCMs' strength and durability compared to CCMs, the use of AAC and HPC remains limited due to the construction cost constraints of RBs. Therefore, we found that using GCM in RBs ensures it meets the performance of CCM while also considering operational and cost-sustainability criteria.

4.2. The Links Between GCM, Residential Buildings, SDGs, and Sustainability Pillars

4.2.1. The Relation Between GCM and the Three Pillars of Sustainability

First, we found that sustainability indicators for using GCMs for RBs were 36 indicators on LR and were supported by the Egyptian building code and the concrete code, green building rating systems [7,33,34,45,51,62,71,81,99,100]. Therefore, the environmental indicators are reduced CO_2 emissions, waste generation, water consumption, natural resource consumption, pollution, and energy use. In contrast, economic indicators focus on the monetary aspects, such as the cost of the final project, property, and maintenance. However, these are influenced by production processes, transportation costs, raw material sources, local availability, building methods, and technology. Although many indicators had regional and geographic limitations and were always measured under the constraints of the same building and concrete codes, others are considered global standards. Figure 4 presents the GCM-SI list and its categories, organized by the three sustainability pillars. The benefits of applying GCMs in the Egyptian RB sector underscore the importance of investigating its contribution to achieving sustainable development [52,101]. Therefore, integrating two sustainability perspectives (three pillars and SDGs) provides a solid context for examining the ability of GCMs, especially for the Egyptian RBs, by selecting those with solid linkages and favorable balancing between the three sustainability pillars to validate the selection indicators, which will be addressed in detail in the next section. Consequently, the linkage between each pillar and its indicators was identified to trace causal relationships [76,102,103].

4.2.2. The Final GCM-SI Selected List for Egyptian Residential Buildings

The final GCM-SI list for investigating the effects in the Egyptian RB sector was identified. We identified indicators for analysis, linked to the three pillars and the relevant SDGs, with each pillar comprising nine indicators. However, the GCM-SI has a different contribution score scale from SDGs; therefore, we focused on identifying the high- and low-contributing areas. This study employed an analysis that identified and combined the 27 GCM-SIs (Table A1) using a weighted sum for each indicator to evaluate GCM sustainability. Therefore, the evaluation was applied using equal weights for sustainable indicators (SIw = 1.000) for simplicity and dimensional equality. Thereby, the GCM-SI weights were calculated by using the following formula:

$$\mathrm{Wi} = SIw/N$$

where the Wi: stands for GCM-SI weight, the Siw is the weight assigned per SDG, and N is the number of GCM-SI and SDG contributions (high or low). For example, in the weighting process for high levels (including high and very high) in the environmental pillar and SDGs, the GHG indicator was assigned a weight (Wi) = 0.22, since (N) = 9 and the participation (SIw) = 2.

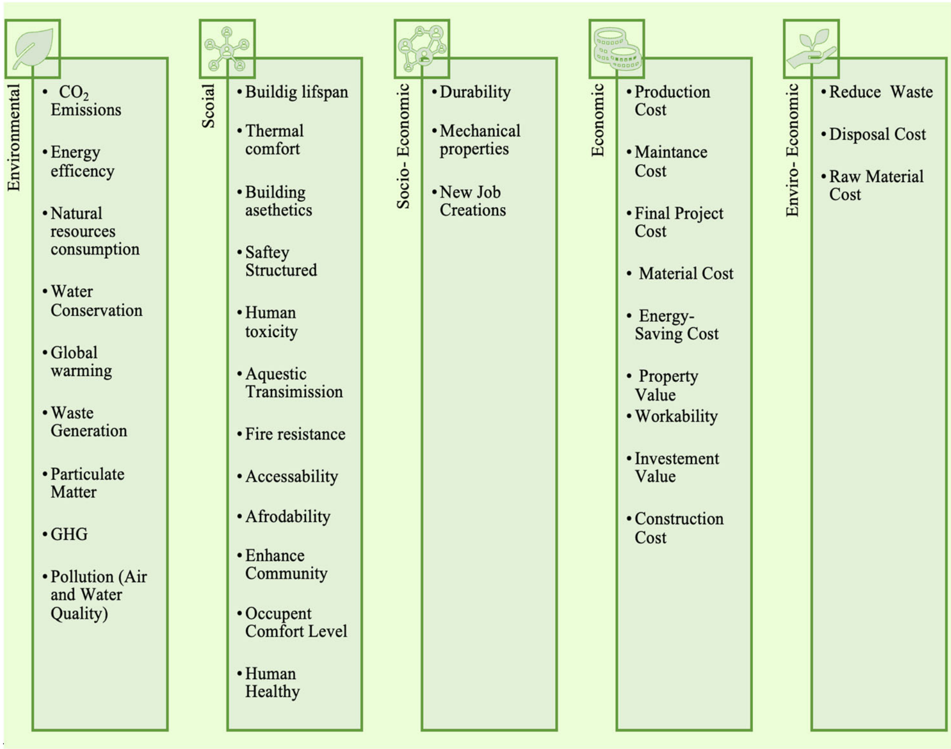


Figure 4. Dimensions for green concrete material sustainability indicators (GCM-SI) for residential buildings.

Environmental Sustainability Pillar of Green Concrete Materials

The environmental indicators in the current study focused on sustainability effects of GCM usage for residential buildings at the local and regional levels, which have strongly contributed to the built environment. In this context, the cradle-to-gate natural resources and energy consumption of CCMs, which encompasses extraction, production, and transportation, have a severe negative environmental impact. Therefore, substituting fossil fuels and natural resources with renewable energy and recycled materials should be considered to ensure sustainability [4,35,104–106]. The use of GCM strategies, which include the recovered and recycled by-product waste materials such as FA, SF, rice husk ash, glass powder, plastic, bricks, rubble, concrete debris, and recycled water in the RB sector, reduces the depletion of natural resources, thereby having a negative environmental impact [86,107]. For example, the negative ecological impact of the cement and concrete industries can be mitigated by reducing natural resource consumption and energy use, as well as by decreasing the CDW stream. Consequently, it results in approximately 50% reduction in GHG emissions [106,108,109]. In the same context, using FA concrete as a partial replacement for concrete containing RAC improved the environmental performance by 53% and FA in NAC by 47%, when water was excluded, compared with the CCM [49], which is recommended for in situ applications in residential projects, depending on the selected building parts [26,110]. Finally, we found that using GCMs in residential buildings improves environmental performance and reduces the severe consumption of CCMs' natural resources (water, sand, and aggregate).

Economic Sustainability of Green Concrete Materials

Using GCM for RBs offers several economic benefits. For example, it can reduce the final cost of concrete materials when recycled materials are used as a whole or partial substitute for natural raw materials. The cost is calculated based on the reduction in primary energy required to produce concrete raw materials per functional unit. Furthermore, the cost of recycled waste materials and alternative binders used in GCMs is linked to solid-waste disposal costs, as these materials are incorporated into the concrete mix. For example, using RAC and FA can reduce costs by approximately 10% and 20%, respectively. Furthermore, using renewable energy for concrete production can add value and improve the final cost efficiency.

Meanwhile, on-site preparation provides greater cost benefits through reduce, reuse, and recycle strategies. For instance, RAC based on CDW, including concrete derbies, can reduce costs associated with new material production, waste disposal, and raw material production by utilizing waste as a source of new materials. Additionally, onsite preparation allows for custom quantities. In the same regard, increasing durability and building lifespan can reduce maintenance and renovation costs throughout the building's life cycle. Innovative technologies, such as 3D-printed and precast concrete, deliver significant cost savings, expand the number of industries, and open new markets (WGBC); consequently, they enhance labor skills and create new job opportunities.

Social Sustainability of Green Concrete Materials

However, a few publications have investigated the social assessment of concrete materials. In the case of RBs, we found a strong association between GCM use and building lifespan. Notably, the social life cycle assessment (S-LCA) is a new technique that complements LCA and LCC; thus, further investigation and improvements are needed. We found that the strong link between social sustainability and use of GCMs depended on integrating RBs' social role in providing inhabitants with safety and good environment, based on green building materials criteria [62,98,111,112]. Because of the variety of GCM types used for different roles in residential applications, many of these materials can positively affect social sustainability indicators, including human health, safety, security, building lifespan, thermal comfort, building aesthetics, human toxicity, acoustic transmission, and fire resistance. For example, human toxicity is strongly related to waste generation and disposal methods, and the high quality of GCMs contributed positively [6].

Furthermore, improving GCMs' market conditions by providing skilled, trained laborers may enhance the social performance of GCMs [113]. Therefore, providing site safety regulations that protect labor conditions has received significant attention, which is considered a positive effect of GCMs' social sustainability. This issue warrants greater attention through the development of new GCM rules and regulations aligned with the Egyptian National Development Strategy 2030.

All Sustainability Pillars

Several indicators have multidimensional contributions, encompassing more than one sustainability pillar. Based on previous definitions and the description of GCM-SI, we found that the distribution of indicators for use in RBs reflects economic, social, and environmental sustainability pillars at 33%, 27%, and 24%, respectively (Figure 5). Additionally, several indicators were combined into the Socio-Economic (Soc-Eco) and Social Environment (Soc-Env) indicators, which accounted for 8% of the total. For example, GCMs' durability and strength have contributed to improved Soc-Eco indicators, lower property costs, and the creation of new markets and jobs. Meanwhile, Soc-Env improvement is found in disposal and recycling material costs. However, the GCM state indicators were found to represent all dimensions of sustainability. Still, this distribution of the GCM-SI provides opportunities to enhance the underperforming pillar by optimizing GCM indicators representing the RBs sector.

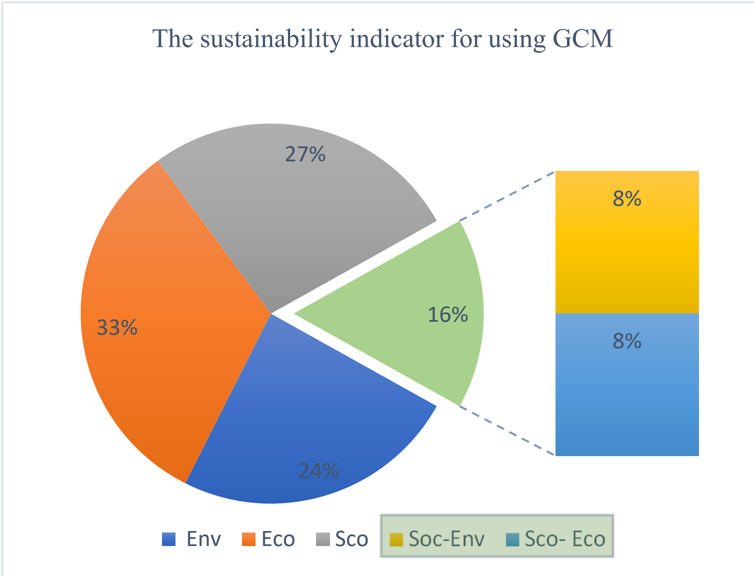


Figure 5. The distribution of GCM indicators and sustainability dimensions.

4.3. Green Concrete Material Sustainability Indicators for Achieving Sustainable Development Goals

In this section, we consider SDGs as a structured basis for defining GCM sustainability indicators and distinguishing between differences and similarities [22,61,62,99,111,114–119]. We identify and investigate the network of SDGs and their targets, as proposed by Le Blanc [76], identifying the link between the network of SDGs and their targets, the GCM and SDGs, followed by defining GCM-SI based on SDGs and three sustainability pillar perspectives [74,75].

However, we found that using GCMs for RBs aligns with most of the SDGs; still, it is necessary to investigate the comprehensive classification of their indicators and to understand their direct and indirect relationships with sustainability. We applied the assessment based on specific indicators, including CO_2 emissions, energy efficiency, raw material consumption, recycled material use, waste generation, pollution, and building lifespan. Furthermore, we integrated several methods to assess indicators of GCM types and strategies based on the suitability of residential typology features.

4.3.1. CO_2 Emissions and Energy Efficiency

Increasing concrete and cement consumption to meet the massive demand for RBs is strongly linked to climate change and its associated extreme risks. The cement industry accounts for 8% of global anthropogenic CO_2 emissions and 3% of the world's energy use [19]. Therefore, it is essential to implement concrete policies to reduce emissions from cement and concrete. We found that GCM directly contributes to SDGs 13, which include urgent action to combat climate change and its impacts, and targets 13.2, hence mitigating climate hazards by reducing GHG emissions and eliminating non-renewable energy use. Furthermore, substituting cement and other raw materials with eco-friendly alternatives is possible [120,121]. Accordingly, SDG9—target 9.4 "CO_2 emission per unit of value-added" and SDG13—target 13.2. "Total GHG emissions per year" directly contribute to CO_2 emissions based on the National GHG Inventory Guide by IPCC [122]. In the same context, SDG 7, "Affordable and Clean Energy," contributes to the energy efficiency strategy through the RB's life cycle from two perspectives: first, reducing concrete material production energy and selecting green alternative materials to optimize the building energy performance and occupant's comfort level during the operation phase. Therefore, it enhances the environmental performance of GCM use across different structural and non-structural RBs parts, supporting the sustainability assessment of the building's lifetime [119]. Second, reducing CO_2 emissions through energy-efficient GCM utilization supports the development of innovative technologies and sustainable practices in manufacturing, providing an effective cost-saving measure for materials that can help achieve SDG7 and its targets (7.3 and 7.2) [123]. Furthermore, SDG11—target 11.6, which includes reducing and mitigating air pollution and GHG emissions, supports the use of a wide range of GCMs for construction applications in new cities and infrastructure [11,124].

4.3.2. Building Materials Efficiency

Generally, the construction industry accounts for approximately half of the global natural aggregate production, consuming around 30–50 billion tons per year (UNEP-GRID 2019). Therefore, GCMs' positive, direct, and substantial contributions to SDG12 "ensure sustainable consumption and production patterns" by recommending increasing the use of recycled materials and alternative aggregate materials as SCMs reduces the challenge of massive raw material consumption. These materials employ resource-efficient strategies and align directly with targets 12.2 and 12.5 by substantially reducing raw material consumption through reuse, recycling, and other waste-reduction measures [42]. Consequently, they are essential in sustainable procurement for residential construction practices. In contrast, GCMs can reduce CDW, eliminate pollution, enhance cost-effectiveness, and address urbanization challenges and obstacles in both developing and developed countries over the coming decades [30,32,48,125].

4.3.3. Waste Generation

The GCM waste generation indicator, which concerns waste management strategies, can be directly aligned with SDG12 "Responsible Consumption and Production" targets 12.2, 12.3, and 12.5 by reducing CDW generation, promoting sustainable management, and improving resource efficiency. Therefore, GCMs align with targets 12.5 (Reduce waste generation), 12.3, and 12.2 by implementing national waste management plans and programs that use the (reduce, recycle, reuse) approach through a cradle-to-grave approach. Furthermore, GCMs facilitate on-site utilization, which is key for minimizing and controlling increasing waste generation and achieving sustainable consumption. In the same context, the use of recycled CDW can contribute to target 3.9 by reducing air pollution from open-air landfill disposal [56,88,125–127].

4.3.4. Occupants' Healthy Lives and Building Lifespan

To achieve SDG 3, "ensure healthy lives and promote well-being," there is a strong link between the use of eco-friendly materials and reduced human health risks, as approximately 1 in 4 deaths globally are attributable to environmental risk factors. Although people spend most of their time indoors, indoor air quality accounts for approximately 90% of their exposure to pollutants [128,129]. Therefore, using GCMs in RBs as eco-friendly materials with optimal physical and chemical properties across components such as walls, floors, ceilings, and indoor finishes provides a healthy indoor environment. Notably, it ensures compliance with the concrete code and green materials specifications, providing high performance in terms of strength, durability, safety, fire resistance, and erosion resistance. Additionally, selecting an appropriate GCM for indoor finishing provides occupants with a sense of comfort regarding indoor air quality, thermal comfort, and visual comfort.

Accordingly, the World Health Organization (WHO, 2016) reduces the need for conventional roofing and flooring coatings, including those that emit hazardous air pollutants from low-quality finishing materials, which can cause lung, central nervous system, and liver diseases. Despite this, few scholars have examined the relationship between indoor building aesthetics and quality and their impact on occupants' mental health and lifestyle. For example, reducing negative environmental impacts and providing a healthy, safe environment can reduce diseases such as anxiety and depression [128]. Therefore, the realization of the SDG 1 target. 1.4 ensures that urban quality of life is a right for all [98,112,114,115,130]. Meanwhile, it reduces the number of vulnerable people living in dangerous homes who are exposed to extreme environmental disasters. Furthermore, using GCMs produced by local, responsible suppliers efficiently utilizes natural resources by partially replacing cementitious materials and natural aggregate, and can reduce final construction costs compared with CCMs [78,131]. Therefore, durable, high-strength concrete materials are essential for optimizing the service life of RBs. Consequently, using GCMs in low-income households as a safe, durable material enables achieving SDG 1 target 1.5 [132,133].

4.3.5. Enhance Communities, Innovation, Technology, and Built Environment

Replacing conventional materials with green and conscious materials promotes urban quality-of-life sustainability, which is considered the key element of SDG 11, "Sustainable Cities and Communities," and can reduce CDW, thereby reducing the negative environmental impacts of cities, which contributes to target 11.6 [134]. Meanwhile, in SDG 9, "Industry, Innovation, and Infrastructure," the GCM is linked to target 9.5, which supports research, development, and innovation in advanced sustainable construction materials [26,135].

4.4. Proposing the Framework for Green Concrete Materials' Contribution to Achieve SDGs

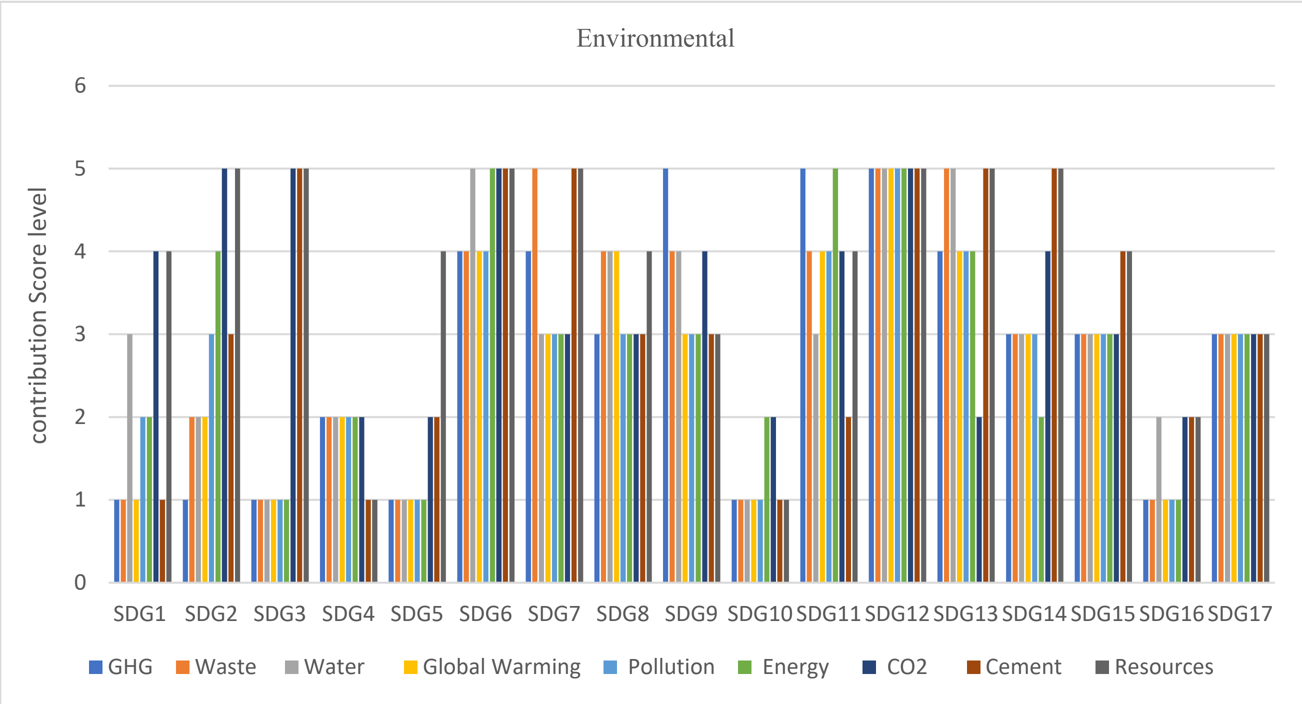
This section examines the relationship between SDGs and the three pillars of sustainability. We found that the use of GCMs significantly contributes to achieving SDGs. Overall, the results indicate the potential for GCMs to mitigate environmental, economic, and social challenges and to promote sustainability in the RBs sector. Therefore, Figure 6 identifies the contribution of GCM-SI to three sustainability pillars and to the SDGs, based on the five points identified in Section 3.2. In this regard, the interdependence among SDGs was noted, with SDG 17 serving as a constant across all pillars. We found that 13 goals contributed to (high & very high) levels in the environmental sustainability pillar, and 12 were found in both the social and economic pillars, as shown in Figure 6. Notably, the most relevant goals with high contributions include the three sustainability pillars in their targets.

4.4.1. Green Concrete Materials' High Contribution

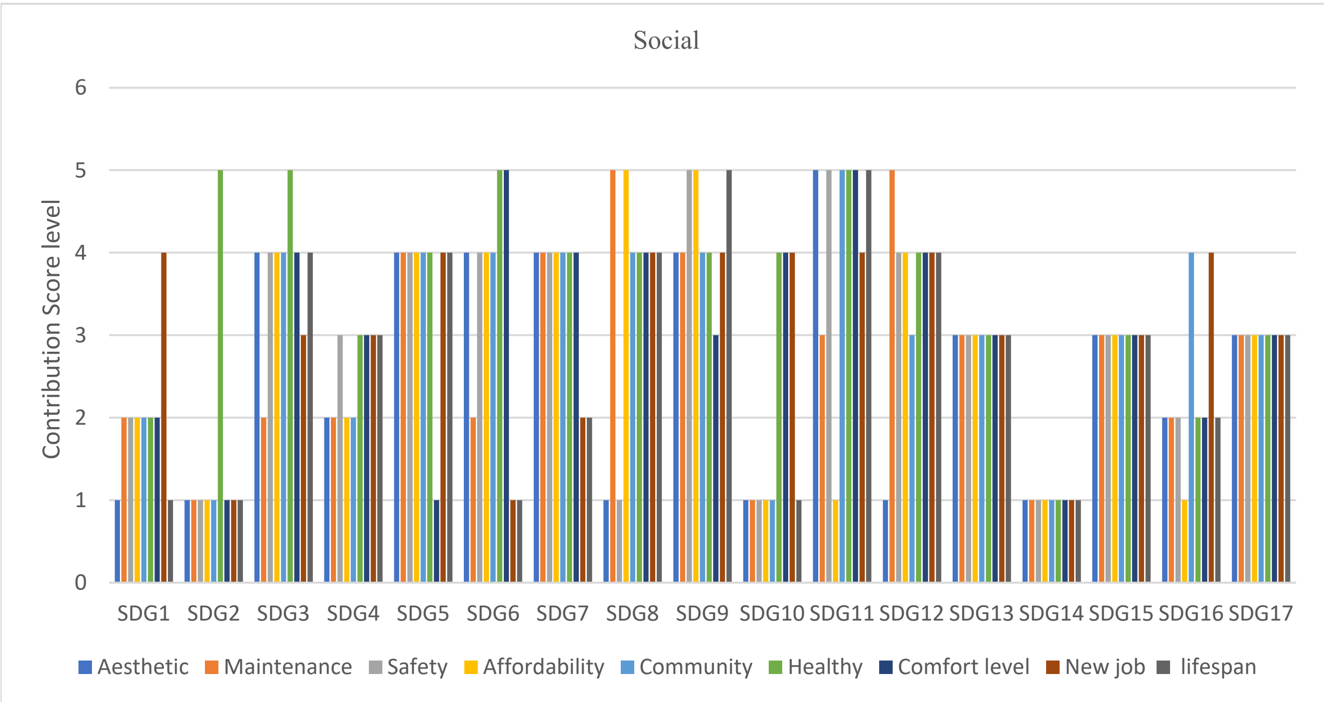
The high contribution level indicates that GCMs make a strong contribution to achieving several SDGs; GCM-SI has significant direct and indirect participation in achieving these goals. As shown in Figure 7, the GCM-SI environmental contribution was high in SDG6 and SDG12 [42]. Otherwise, GCM-SI contributed to economics with SDG3, SDG8, SDG9, SDG11, and SDG12, and socially contributed to SDG5, SDG9, SDG11, and SDG12. The results indicate that using GCMs in RBs poses challenges when SDGs and the sustainability pillars of the overall strategy are not taken into account. The high value indicates that these make a significant contribution to SDGs.

4.4.2. Green Concrete Materials' Low Contribution for SDGs

Otherwise, the contributions are identified as light and dark yellow, as shown in the Section 3.2.1, corresponding to low and very low contributions, respectively. They are clarified in environmental, social, and economic pillars by (SDG4, SDG10, SDG16), (SDG14, SDG1, SDG2, SDG16), and (SDG4, SDG5, SDG14, SDG15, SDG16) respectively, which are considered an obstacle needs for more investigation efforts and new rules and regulations for using GCMs in RBs to achieve SDGs. Accordingly, Figure 8 illustrates GCM-SI's lower contribution, which is considered an opportunity to evaluate the material's performance and enhance it through sustainability pillars. The high value indicates that these goals have a low contribution to SDGs.

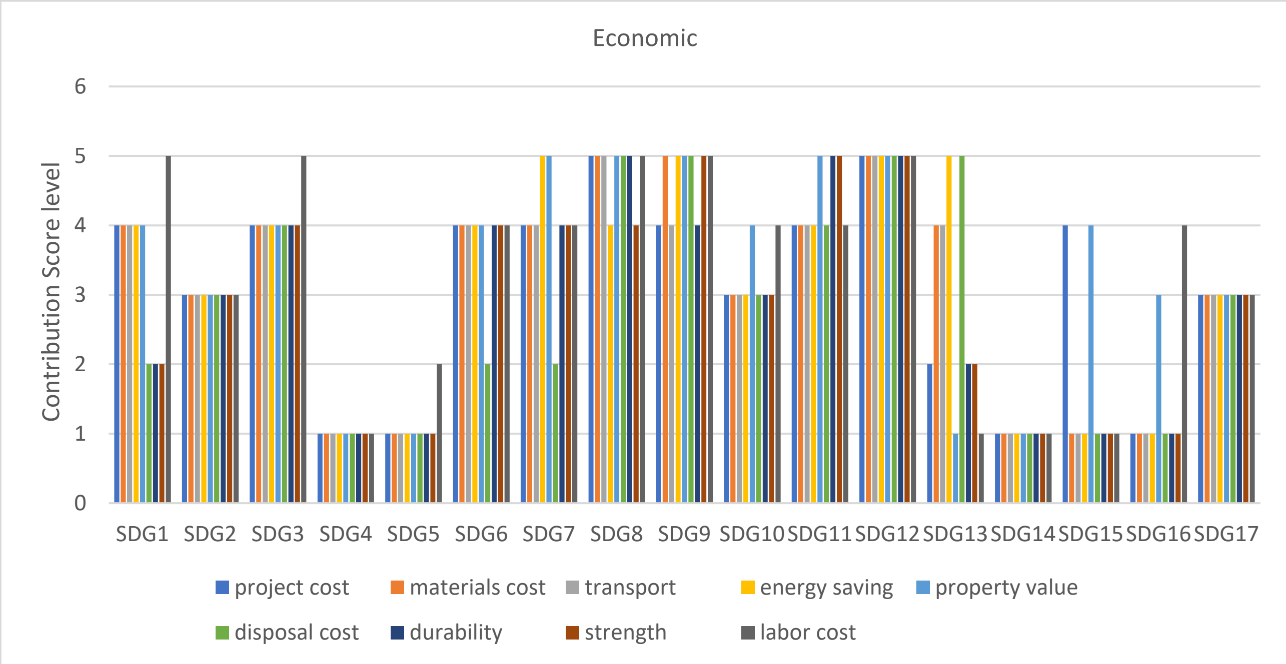


(**a**)



(**b**)

Figure 6. *Cont.*



(**c**)

Figure 6. The contribution of GCM-SI to three sustainability pillars and the SDGs: first, environmental indicators (**a**), social indicators (**b**), and economic indicators (**c**).

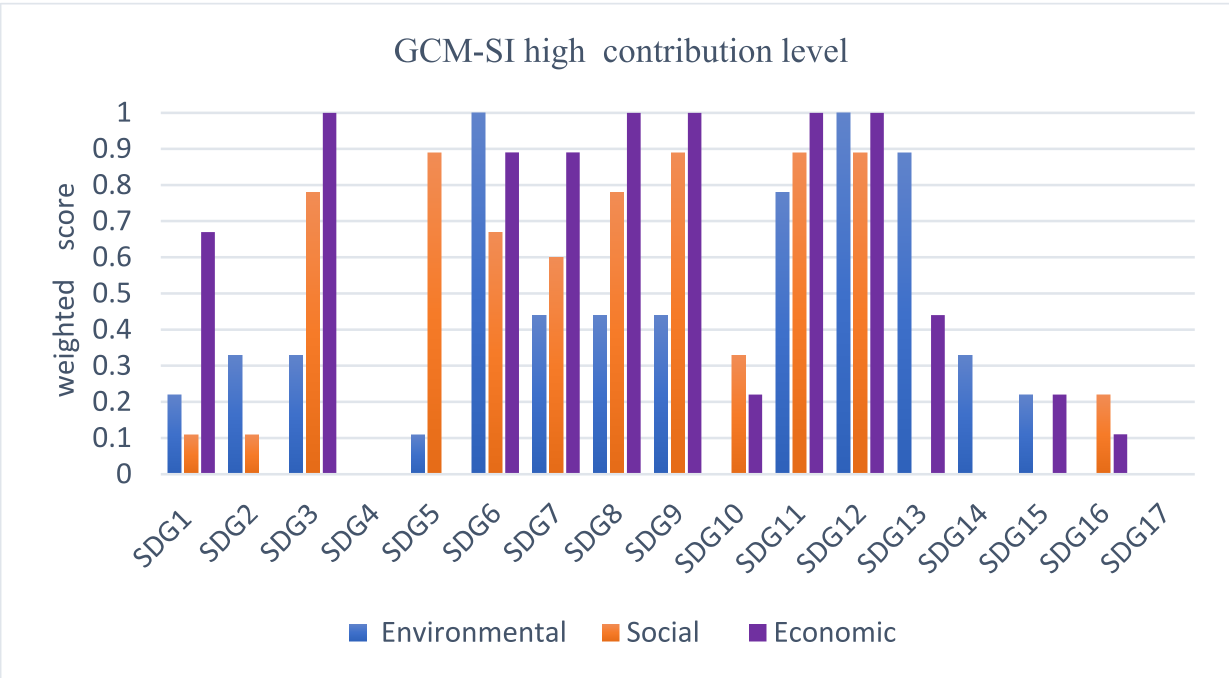


Figure 7. The high level of contribution between SDGs and GCM-SI.

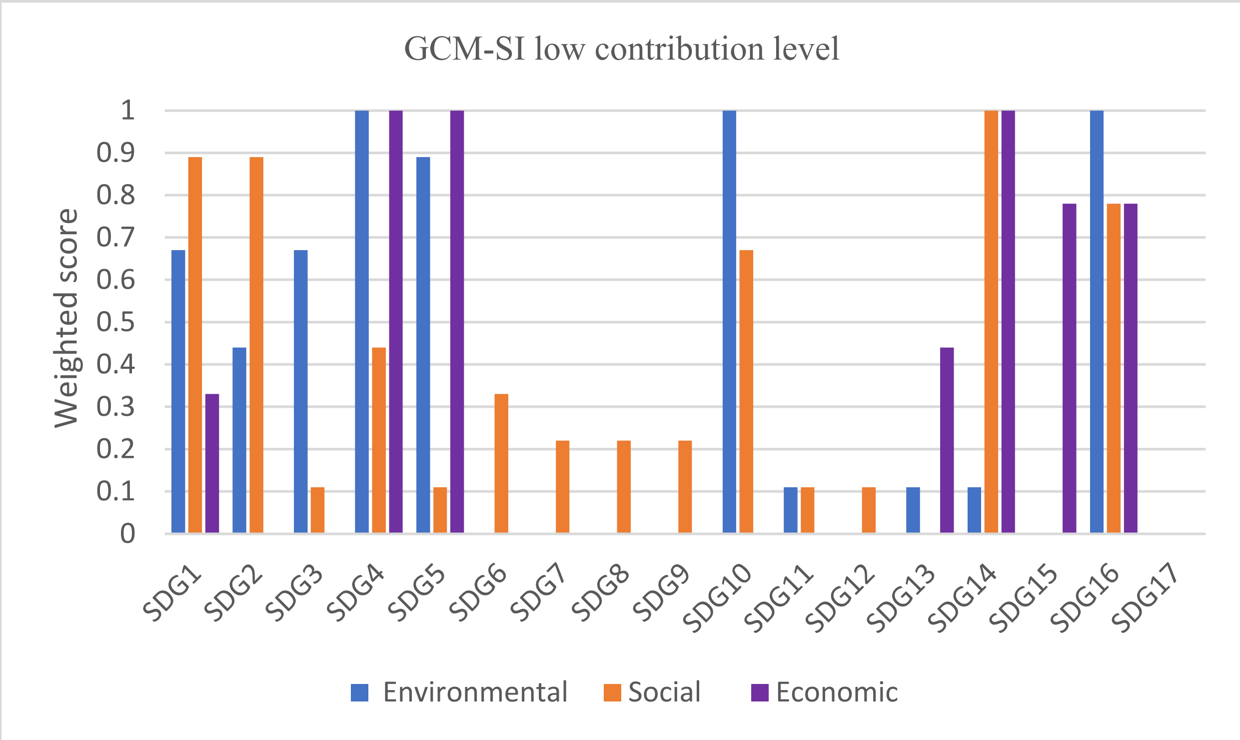


Figure 8. The low level of contribution between SDGs and GCM-SI.

4.4.3. The Relation Between Most GCM-SI and SDGs

However, SDGs are considered a network of targets; the inner links between SDGs through targets should be regarded as a means to realize the 2030 Agenda. Therefore, we identified a high contribution between GCM-SI and SDGs. In the same context, to further investigate high-level contributions (high–very high), we constructed a scoring matrix for GCM-SI–SDG across 17 SDGs and 27 indicators within sustainability pillars. As shown in Figure 9, the distribution of the high and very high contribution levels between GCM-SI and SDGs is shown. We found that the use of GCMs in RBs has strongly contributed to SDGs. The most relevant Sustainable Development Goals (SDGs) for using GCMs in RBs are SDG 12, SDG 11, SDG 6, SDG 9, SDG 8, SDG 3, and SDG 7, with percentages of 92%, 85%, 85%, 77%, 74%, 70%, and 70%, respectively. This finding was determined through a threshold-based scoring analysis and counting relationships with $\geq$4 scores. Consequently, it indicates that a larger proportion of the indicator set aligns strongly with that SDG, identifying it as a priority area in which the evaluated indicators most consistently support GCM-related strategies in residential projects. For example, SDG12 achieved a strong contribution level of approximately 92% because 25 of 27 SDG12 indicator relationships were rated High or Very High. This finding shows that responsible consumption and production is the SDG most supported by the GCM-SI indicator set, highlighting its usefulness for prioritizing circular material strategies, such as recycled materials, by-products, and resource efficiency, in early residential design and procurement. On the other hand, the low contribution % scores of 44%, 33%, 33%, 18%, 14%, 14%,11%, 11%, 0%, and 0%, were noticed within the SDG13, SDG1, SDG5, SDG10, SDG15, SDG2, SDG14, SDG16, SDG4, and SDG17, Figure 10 illustrates the contribution percentage between each goal and the GCM-SI.

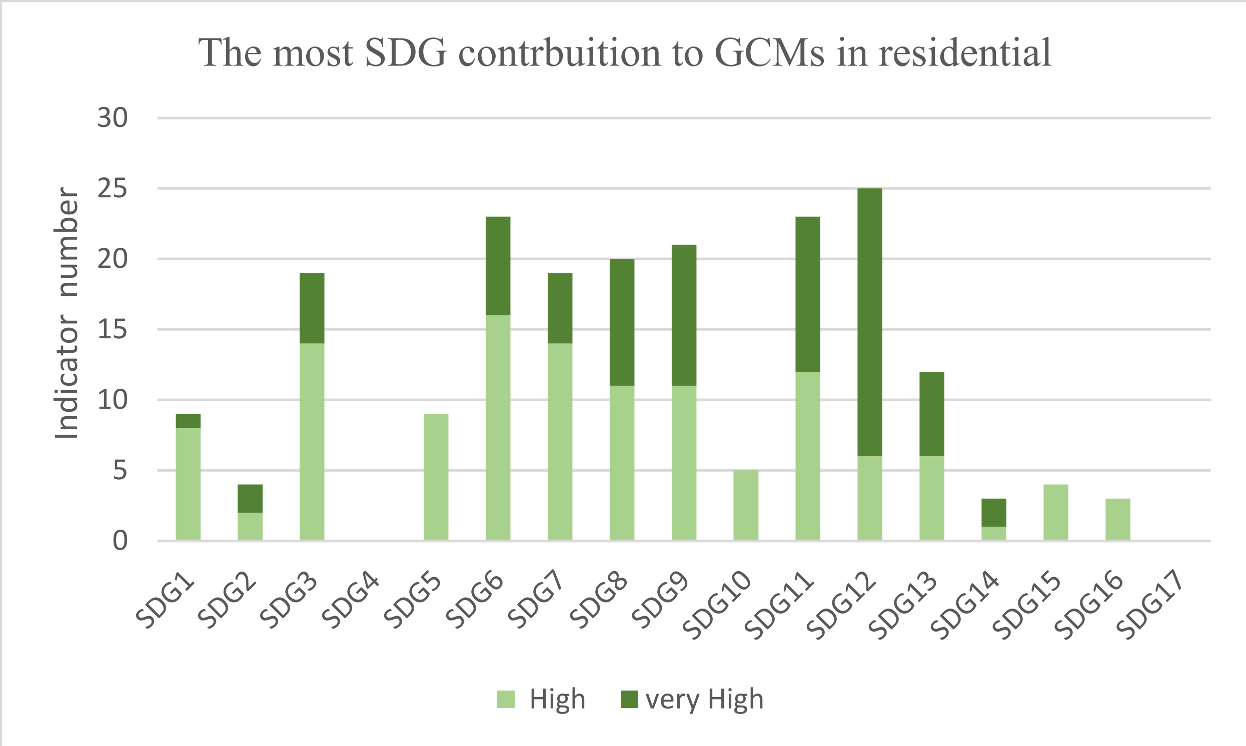


Figure 9. SDGs contribute to high and very high levels.

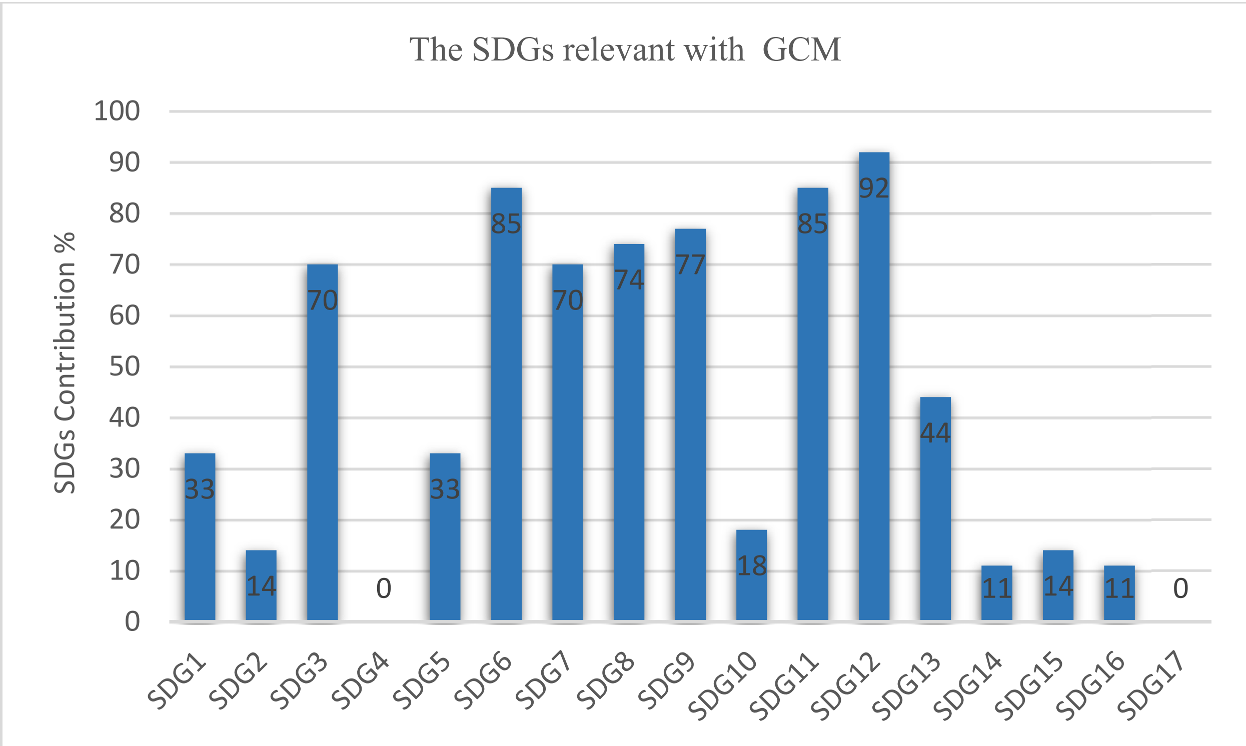


Figure 10. The contribution percentage between each goal and the GCM-SI.

4.5. Develop Green Concrete Materials Sustainability Framework (GCM-SF)

The most significant effects of using GCMs in the residential sector are attributed to SDGs and their corresponding targets. For example, in SDG 3, target 3.3 aligns with efforts to enhance indoor air quality and human health by reducing toxicity through the use of substitute materials for conventional coatings. In this regard, SDG12 supports resource efficiency and reduces pollution and embodied carbon, aligning with target 12.2. It reduces waste generation with target 12.5 and supports the use of friendly construction materials within target 12.8. Figure 11 illustrates the most relevant Sustainable Development Goals (SDGs) and their targets, which are essential to achieving them. Developing a framework provides comprehensive, clear guidelines for the use of GCM in RBs to achieve SDGs. Furthermore, GCM-SF encourages the scalability of GCM contributions to achieve SDGs in future RB projects. Therefore, GCMs are considered eco-friendly, they reduced and eliminated environmental impacts, and improved economic and social aspects compared with CCMs.

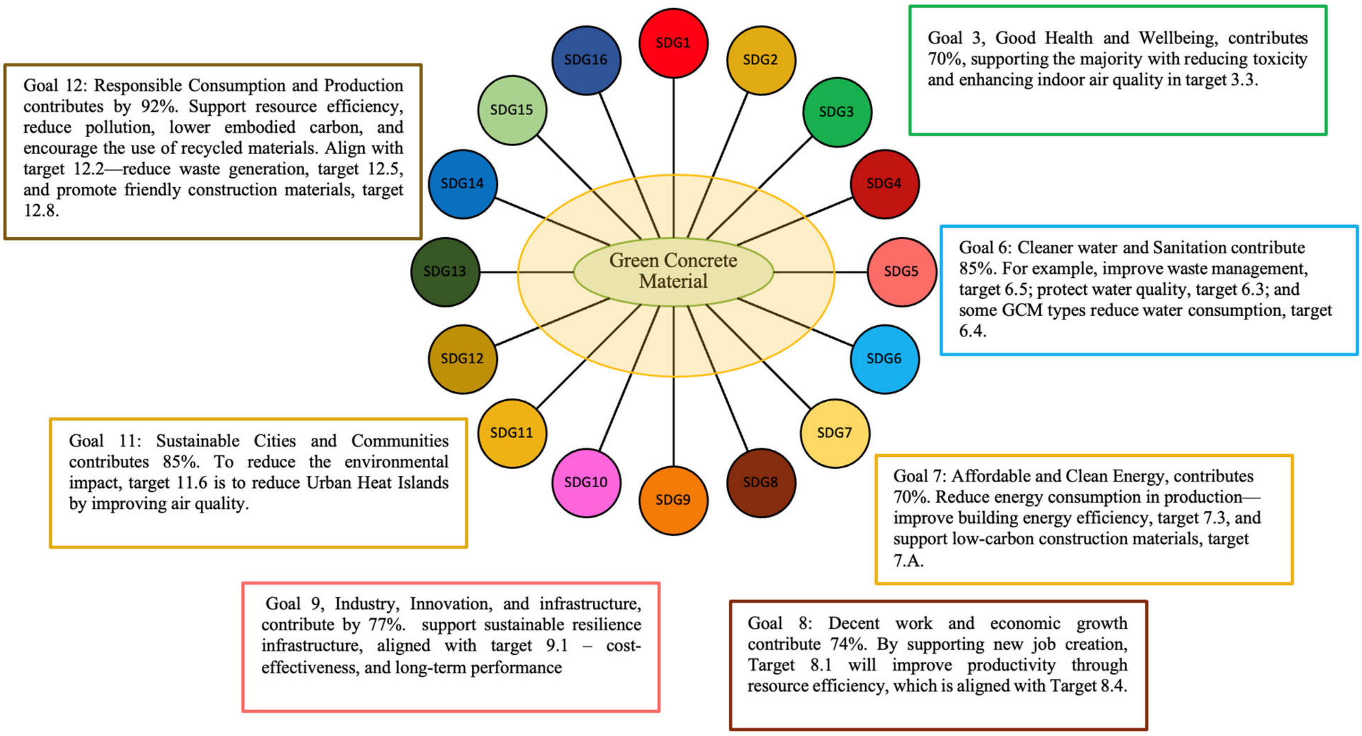


Figure 11. The most relevant SDGs and their targets (source: authors).

The Relationship Between SDGs and GCMs

The framework explains that the percentage of SDG contributions can be understood through the causal pathways by which the use of GCMs influences RB outcomes. Higher contributions are observed in SDG12, which align with the most influential indicators of the framework, as GCM measures target embodied-impact and resource-efficiency mechanisms directly. For example, (reducing cement with supplementary cementitious materials → reducing CO_2 emissions →increasing recycling and by-product use → reducing CDW → achieving circularity → reducing natural resource consumption → enhancing durability →decreasing maintenance → and improving building life service). Conversely, SDGs with lower contributions are influenced only indirectly by material choices and depend more on external enabling conditions such as institutional capacity, education, and broader ecosystem governance, as shown, for example, in SDG4 and SDG14.

5. Conclusions

Developing the GCM-SF was vital to the sustainable development of the Egyptian residential building sector. Therefore, a comprehensive literature review was conducted using a five-point scale, and the contributions of the indicators at different levels were identified to facilitate the understanding of the sustainability relationship. This study integrates the two global sustainability perspectives of SDGs and the three pillars to investigate the role of GCMs in the Egyptian residential building sector in achieving SDGs. The study showed that 27 GCM-SI contributed to the three pillars and SDGs, which were used to develop GCM-SF, a tool to clarify and operationalize GCM's role in achieving SDGs. The higher- and lower-contributing features were identified to address classification difficulties and to investigate the most critical interactions. The framework revealed that GCMs have significantly contributed to 13, 12, and 12 of the 16 goals of the UN 2030 Agenda, after accounting for SDG 17 as a constant goal. These goals align closely with sustainability indicators that focus on improving responsible consumption and production, increasing the efficiency of natural resource use, enhancing occupants' well-being, and building resilient infrastructure and sustainable cities.

On the other hand, the most essential GCM-SI for the environment are reducing natural resource consumption, cement consumption, and CO_2 emissions. Meanwhile, critical social indicators include improvements in human health and enhanced community well-being, whereas economic indicators demonstrate substantial contributions to property values and labor costs. The study found that the significant contributions in high and very high levels are 92% for SDG 12, 85% for SDG 11, and 85% for SDG 6. Meanwhile, the low contribution in low and very low levels was 11% for SDG 14 and SDG 16, using GCMs in RBs. Thereby, the study demonstrates that:

The framework presented an opportunity to simplify the use of GCMs in RB projects by examining the strengths and opportunities that contribute to achieving SDGs.

Sustainability performance is achieved by integrating several GCM characteristics and strategies suitable for residential projects in the early construction stage.

- The integration of SDGs and the triple bottom line facilitates the identification of weaknesses and obstacles, which serve as a starting point for recovering and enhancing the use of GCMs in RBs.
- The social indicators provide an essential framework for using GCMs and highlight the need for further investigation.

Recommendations and Future Research Direction

However, the realization of GCM-SF's benefits is constrained by barriers, including variability in SCMs and recycled input systems, limitations in GCM regulatory frameworks, labor skills, residential cost constraints, acceptance, and the lack of sector-updated data and information. Furthermore, these limitations may indicate that SDG percentages reflect relative contributions under feasible implementation conditions rather than assured outcomes. Therefore, the study recommends that new rules and regulations be formulated and that public and private construction stakeholders cooperate to promote the use of GCMs in RB projects.

Future research requires more data and further investigation to explore the possibility of integrating the knowledge necessary for policy formulation and achieving sustainability. Furthermore, extended testing of the framework's performance across various construction applications is needed.

Author Contributions: Conceptualization, H.M., G.K. and G.S.; methodology, H.M. and G.S.; software, H.M. and G.S.; validation, H.M., G.S. and G.K.; formal analysis, H.M. and G.S.; investigation H.M., G.S. and G.K.; resources, H.M., G.S. and G.K.; data curation, H.M. and G.S.; writing—original draft preparation, H.M.; writing—review and editing, H.M., G.S. and G.K.; supervision, G.S. and G.K. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data produced and processed in this study are included in the published article. In addition, datasets can be acquired from the corresponding author for appropriate purposes.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

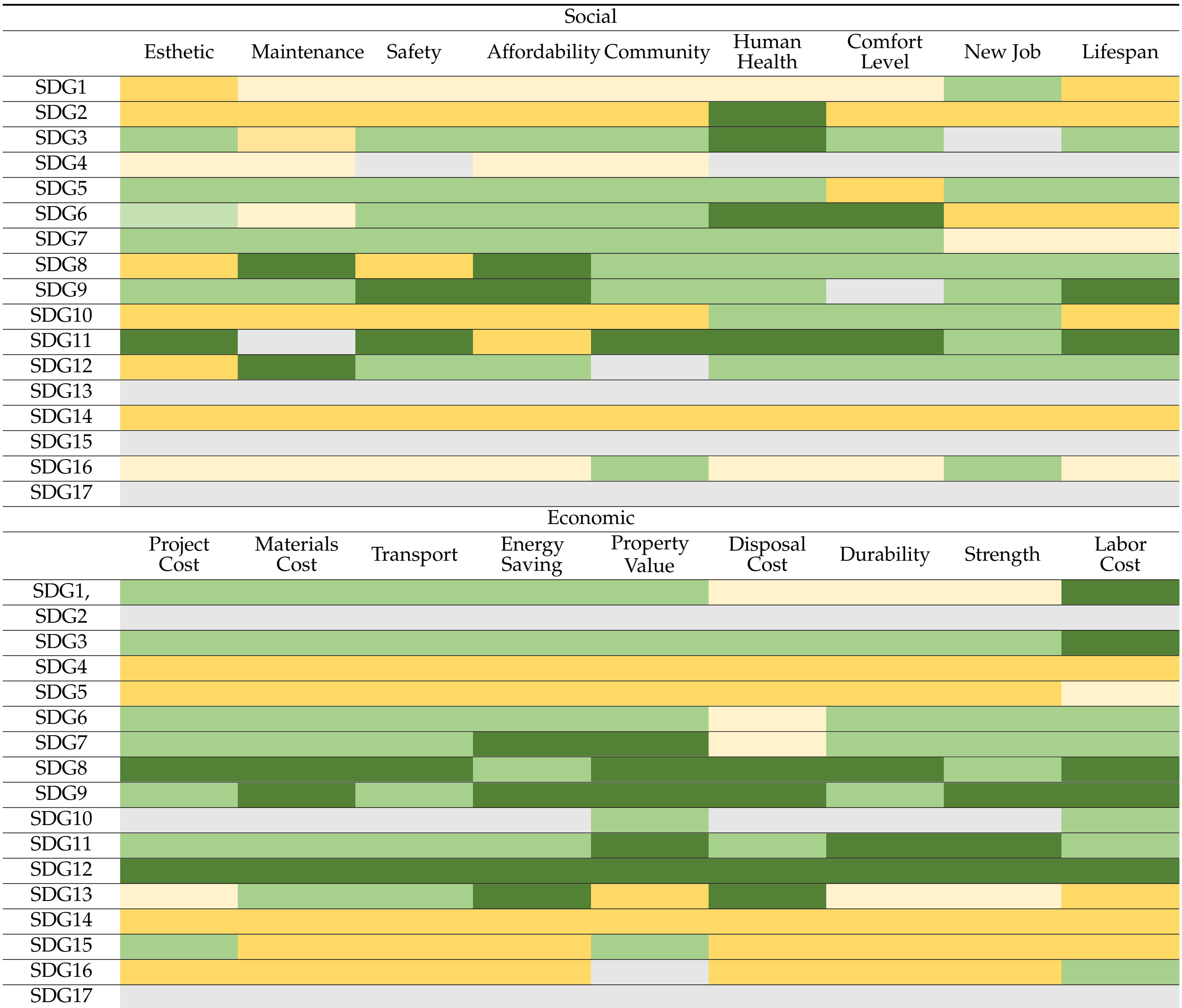
AAC	Alkali-Activated Concretes.
CCM	Conventional Concrete Material.
CDW	Construction And Demolition Waste.
FA	Fly Ash.
GC-SF	Green Concrete Sustainability Framework.
GCM	Green Concrete Material
GCM-SI	Green Concrete Material -Sustainability Indicators.
GGBS	Ground Granulated Blast Furnace Slag.
GHG	Greenhouse Gas Emissions.
OPC	Ordinary Portland Cement.
PCC	Portland Cement Concrete.
RA	Recycled Aggregates.
RAC	Recycled Aggregate Concrete.
RBs	Residential Buildings.
SCMs	Supplementary Cementitious Materials.
SD	Sustainable Development.
SDGs	Sustainable Development Goals.
SF	Silica Fume.

Appendix A

Table A1. Green Concrete material sustainability indicators GCM-SI contributed to three sustainability pillars and SDGs.

SDG12									
SDG12									
SDG12									
	Environmental								
SDGs	GHG	Waste	Water	Global Warming	Pollution	Energy	CO_2	Cement	Resources
SDG1									
SDG2									
SDG3									
SDG4									
SDG5									
SDG6									
SDG7									
SDG8									
SDG9									
SDG10									
SDG11									
SDG12									
SDG13									
SDG14									
SDG15									
SDG16									
SDG17									

Table A1. *Cont.*



Dark yellow (very low), light yellow (low), gray (moderate), light green (high), and dark green (very high).

Very low	Low	Moderate	High	Very high

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